OPTIMIZING THE DOMESTIC CHEMICAL, BIOLOGICAL, RADIOLOGICAL, AND NUCLEAR RESPONSE ENTERPRISE

THESIS

MARCH 2015

Nick Paul, Captain, USA

AFIT-ENS-MS-15-M-143

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT-ENS-MS-15-M-143

OPTIMIZING THE DOMESTIC

CHEMICAL, BIOLOGICAL, RADIOLOGICAL, AND NUCLEAR

RESPONSE ENTERPRISE

THESIS

Presented to the Faculty

Department of Operational Sciences

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

in Partial Fulfillment of the Requirements for the

Degree of Master of Science (Operations Research)

Nick Paul, BS, MS

Captain, USA

March 2015

OPTIMIZING THE DOMESTIC

CHEMICAL, BIOLOGICAL, RADIOLOGICAL, AND NUCLEAR

RESPONSE ENTERPRISE

THESIS

Nick Paul, BS, MS
Captain, USA

Committee Membership:

LTC Brian J. Lunday, PhD
Chair

Sarah G. Nurre, PhD
Member

AFIT-ENS-MS-15-M-143

Abstract

The Chemical Biological Radiological Nuclear (CBRN) Response Enterprise (CRE) exists to rapidly respond to a domestic CBRN attack in order to minimize the overall impact of an incident. Over the past 16 years, the CRE has grown incrementally, and it is unclear if the current locations of units optimizes the coverage of the US population within a rapid response window. In this paper we develop a multi-objective multi-service extension of the maximal covering location problem (MCLP) to analyze the current coverage provided by the CRE and recommend efficient modifications to better protect the American population. While public sector facility location problems are well studied, the significant damage created by a CBRN attack requires unique modeling considerations. Most notably, we model the impact to coverage when CRE units within a minimum stand-off distance are rendered non-functional by a CRBN attack using an adaptation of the conditional covering problem (CCP). This minimum stand-off distance is not currently a consideration in existing Department of Defense (DoD) doctrine or planning guidance, but through a comparison to the current DoD definition of coverage we demonstrate the value of incorporating this concept into future planning considerations. Finally, we account for the multi-objective nature of this problem by developing a set of non-inferior solutions that allow a decision maker to apply their judgment to balance the trade-off between coverage and cost. Overall, this analysis demonstrates the value of incorporating facility location models into future DoD decisions.

Acknowledgements

I would like to express my sincere appreciation for my advisor, LTC Brian J. Lunday for his direction and support throughout the development of this thesis. I would also like to thank Dr. Sarah G. Nurre for her guidance and contribution.

Nick Paul

Table of Contents

List of Figures

List of Tables

OPTIMIZING THE DOMESTIC

CHEMICAL, BIOLOGICAL, RADIOLOGICAL, AND NUCLEAR

RESPONSE ENTERPRISE

I. Introduction

"The most fundamental duty of the Department of Defense is to protect the security of U.S. citizens. The homeland is no longer a sanctuary for U.S. forces, and we must anticipate the increased likelihood of an attack on U.S. soil." [42]

– 2014 Quadrennial Defense Review

1.1 Background

The use of a Chemical, Biological, Radiological, or Nuclear (CBRN) weapon in a domestic terror attack remains one of the nation's most significant security threats. While prevention is the first priority, the nation must be prepared to respond to a domestic CBRN attack. The Department of Defense (DoD) maintains the CBRN Response Enterprise (CRE) to leverage internal assets to support civil authorities in the response to such an attack. The DoD defines the mission for this force as follows:

"DoD will maintain a CBRN response enterprise that balances Federal and State military responsibilities in order to reduce the response times to save lives and minimize human suffering." [15]

Development of the CRE began in the mid 1990s following domestic terror attacks and a perceived gap in the nation's ability to respond to a CBRN incident. Over the

past 16 years, the structure of CRE has rapidly evolved from a force of 300 National Guard personnel in 1998, to over 15,000 personnel comprised of both National Guard and Federal forces. These changes occurred predominantly after government sponsored reports identified gaps in the structure and capabilities. While the force is more prepared than ever to respond to a domestic CBRN incident, the DoD acknowledges improvements in the structure still exist and states it "will continue to improve CBRN force posturing and refine force sourcing processes to meet future national requirements for domestic CBRN incident response" [15]. The initial shaping of the force, driven primarily by qualitative metrics, appears to be reaching its pinnacle and large gains in the response capability provided by the force are less likely. The analysis of the CRE now needs a quantitative assessment to identify refinements in its structure that can produce a more efficient force.

An area that has received little attention is an analysis of the CRE unit locations and how well they cover the population within a rapid response window. While the siting of CRE units was accomplished in a deliberate manner, the incremental establishment of units may have created inefficiencies within the structure. To date there does not appear to be a clear understanding of whether the current location of CRE units optimizes coverage of the population. An analysis of the layout of the CRE utilizing previously proven quantitative modeling techniques can provide a better understanding of the current array's coverage capabilities compared to an optimal structure.

Before further clarifying the scope of this thesis, a description of the units that comprise the CRE is warranted. The CRE has a federal component and a National Guard component that are structured in completely different manners, each worthy of their own detailed analysis. Since the National Guard currently constitutes 70% of the CRE [14], this study will focus on a holistic analysis of the locations of National

Guard CRE elements. The National Guard component of the CRE currently consists of three echelons: Weapons of Mass Destruction Civil Support Teams (WMD-CSTs), CBRNE Enhanced Response Force Packages (CERFPs), and Homeland Response Forces (HRFs). The following paragraphs provide a brief description of the capabilities of units at each echelon.
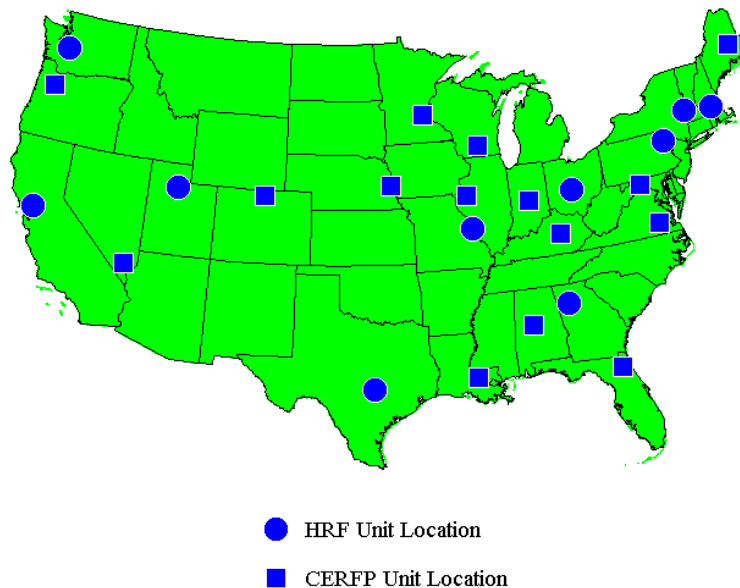
Figure 1. Unit Location of CERFPs and HRFs

WMD-CSTs constitute the first response of the CRE. Their primary mission "is to assist in identification and assessment of CBRNE hazards and advise first responders and follow on forces" [15]. There are currently 57 WMD-CSTs with at least one in each state and one in, Washington D.C., Guam, Puerto Rico, and the Virgin Islands. (Henceforth, we use the term *state* to generically refer to a state, commonwealth,

territory, protectorate, or district.) Florida, California, and New York each have two based on their large populations.

First instituted in 2004, the CERFP is the next level of response at the state level. Their capabilities, as described in Joint Publication 3-41, consist of "casualty search and extraction, emergency medical triage, treatment, and patient stabilization, and mass casualty decontamination, in a contaminated environment" [35]. There are currently 17 CERFPs located across the United States, as illustrated in Figure 1, with at least one per Federal Emergency Management Agency (FEMA) region. The states located in each FEMA region are depicted in Figure 2. Each CERFP is comprised of approximately 186 personnel.
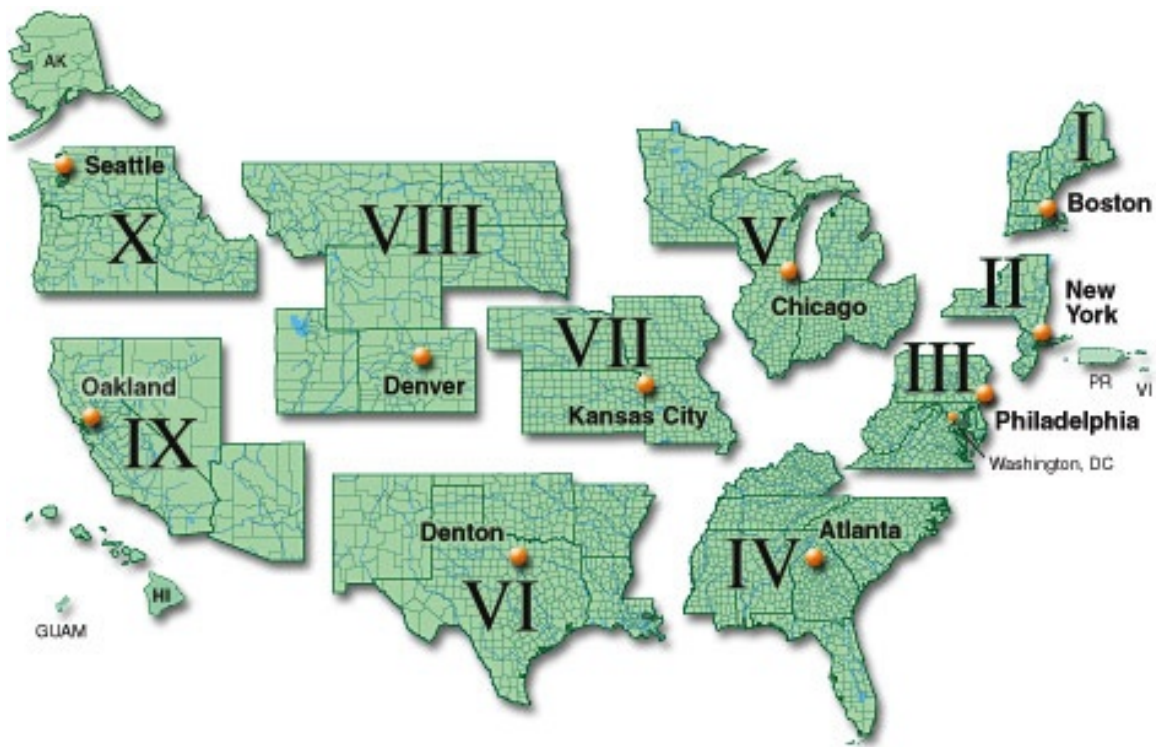
Figure 2. FEMA Regions [19]

The final element of the state response, the HRF, was first instituted in 2012. Each HRF consists of roughly 570 personnel, provides the same capability as a CERFP,

but also adds a brigade-size command and control headquarters and a battalion-size security component. According to the Government Accountability Office (GAO), a HRF is designed to manage up to five CSTs and three CERFPs [59]. There are currently ten HRFs, one aligned with each FEMA region, at locations as illustrated in Figure 2.

1.2 Problem Statement

The location of each WMD-CST, CERFP, and HRF impacts the CRE's ability to rapidly respond to a CBRN incident. Rapid response is critical to saving lives and minimizing human suffering, which is at the core of the CRE mission. While the current array seems sufficient, it is unknown if a better configuration exists. Furthermore, the structure of the CRE was established incrementally and has never been fully analyzed as a whole. The current distribution of these units needs to be assessed to determine how well they currently cover the population within a rapid response window. Additionally, given the current fiscal climate, a balance between costs and capability is required; added costs must result in a significant gain in response capability provided to the population. Finally, the proximity of some CRE units to large population centers places these units at risk of being crippled by a large-scale CBRN incident. The inability of the closest CRE unit to perform their assigned mission would lead to a dramatic increase in response time and could lead to additional deaths and suffering. Options need to be explored that minimize this risk. Thus, we seek to develop CRE unit locations that maximize the population covered in a rapid response window while minimizing the cost of modifications to the existing structure and reduce risk to CRE units.

1.3 Approach

To date, there is no published research applying facility location models to analyze the CRE. Facility location problems have been, however, utilized extensively in the siting of Emergency Response Services (ERS) facilities, such as fire and police stations [20] [40] [45] [47] [57] [60]. Siting CRE units and ERS facilities share many similar objectives and constraints that encourage the use of similar mathematical modeling techniques. Thus, we include a commonly utilized ERS objective that maximizes the population covered for a fixed set of assets (i.e., a Maximal Covering Location Problem (MCLP) [27]) in the model development. To account for costs, we develop a set of non-inferior solutions that identify the trade-off between coverage gained and modifications to the existing structure. Finally, elements from the conditional covering problem (CCP) [26] [50] are included to model the impact of a CBRN event rendering a CRE unit non-functional within a minimum stand-off distance.

1.4 Assumptions

To narrow the scope of this thesis, several assumptions are required. This section covers our general assumptions about the CRE and its capabilities to define the limits of the analysis. More specific assumptions are presented in Chapter 3 that relate specifically to the model development.

Outside the scope of this study is an examination of the division of the the CBRN Response Enterprise into three echelons and the respective capabilities that exist at each echelon. Furthermore, we assume that these units provide the necessary capability desired to respond to an event. Clearly, this assumption relies upon external factors such as the type and magnitude of a given CBRN event and the readiness of the CBRN forces. Should the structure of the force be changed to include different echelons and capabilities, the foundation of the analysis would still hold true, requir-

6

ing only adjustment to some of the specific model parameters to remain informative.

1.5 Summary

This chapter highlighted the exiting CBRN threat, the CRE, its core components, and a gap in the current analysis of its structure. The goal of this analysis is to apply mathematical modeling techniques to assess the current structure's influence on rapid response. The model also considers costs and identifies the impact to coverage if CRE units are rendered non-functional by a CBRN incident within a minimum stand-off distance. Finally, key assumptions were presented that limit the scope of the analysis.

In the following chapter we highlight the existing literature relevant to the CBRN Response Enterprise and facility location models that are necessary to inform the analysis. In Chapter 3 we provide the formulation of our model and justification for parameter estimates. The analysis of results and a model extension are presented in Chapter 4. Finally, in Chapter 5 we present significant insights and areas for future research.

II. Literature Review

2.1 Overview

This chapter reviews previously published doctrine and research focused on the CBRN response enterprise (CRE) and facility location modeling. The CRE literature provides a historical overview of the development of the CRE, demonstrates the importance of the CRE within the DoD, familiarizes the reader with its basic employment, and discusses the current standards for coverage. Additionally, we demonstrate the limited quantitative analysis of the existing CRE structure. Finally, facility location models and their application that inform our model developed in Chapter 3 are reviewed.

2.2 CRE Development

The origin of the CRE started with the Defense Against Weapons of Mass Destruction Act in 1996. This Act required the improvement of domestic preparation and response capability to a CBRN attack [5] and provided funding for the development of response capabilities. As a result, the DoD was directed to develop a strategy to leverage its internal capabilities in support of CBRN response. The initial strategy was modeled to support response to events similar to the 1993 World Trade Center bombing and the 1995 Tokyo Sarin gas attack. In 1997, the Undersecretary of Defense directed the investigation of integrating the National Guard and reserve components for CBRN response [5], and in 1998 this initial plan for integration was approved. It began by establishing ten WMD-CSTs (initially referred to as Rapid Assessment and Initial Detection (RAID) teams), one in each FEMA region. These WMD-CSTs were state controlled National Guard assets that would assist local responders with detecting the presence of CBRN effects and estimating their impact.

Over the next nine years additional teams were established such that, by 2007, each state or territory sourced a certified WMD-CST based within their boundaries [30].

Each WMD-CST consists of 22 full-time personnel who serve in a Title 32 status from the Army and/or Air National Guard[1]. Teams are controlled by the sourcing state but are able to respond to incidents in other states, either through state coordination or federalization by the President of the United States [36].

As analysis of the CBRN consequence management continued, the DoD recognized there were still gaps in providing initial decontamination and search and extraction to an overwhelmed local response. CERFPs were first developed in 2003 to fill this gap and were modeled on an existing CBRN response force in the Marine Corps. In 2004, 12 teams were established, with at least one in each FEMA Region; an additional five teams were added in 2006. It is not clear from the open source literature why 17 CERFPs was deemed to be the appropriate number of units. In fact, a RAND report from 2010 suggested there was not a clear understanding of the capabilities required to respond to a CBRN incident and that the current structure, while useful, had not been fully analyzed [1]. This seems to suggest that the number of CERFP units needed may not be fully understood. While outside the scope of this research, a future study could analyze how the existing capabilities of the CRE would support a CBRN incident based in terms of expected throughput of decontamination, search and extraction, and medical triage.

As mentioned before each CERFP consists of approximately 186 personnel drawn from pre-existing units from the sourcing state, and each unit within the CERFP maintains its organic mission along with the CERFP mission. A unit is described as pre-existing because it was not specifically created to serve as a component of the CERFP, and the organic mission is the mission the unit prepared for prior to it

---

[1]Title 10, USC (under federal control and federally funded); Title 32, USC (under state control and federally funded); and state active duty (under state control and state funded).

assuming the additional mission as a CERFP component. For example, the search and extraction element of the CERFP is commonly drawn from an engineer company within a sourcing state. The engineer company trains to serve as the search and extraction component of the CERFP, and it also trains for its organic engineer mission. Unlike WMD-CSTs, the personnel assigned to a CERFP are maintained in a reserve status[2] and are mobilized in response to an incident. Additionally, a CERFP can consist of units sourced from different states.

In addition to CERFPs, the DoD also began to establish a response force from the federal forces called the CBRN Consequence Management Response Forces (CCMRF). The initial plan called for three CCMRFs, each a brigade size unit consisting of approximately 4,500 personnel drawn from different federal units across the country. The CCMRFs were designed to serve as the next layer of response after the CERFP. Given the geographic dispersion of the force, the expected response time for this force was 48-96 hours after notification [32]. In the 2010 Quadrennial Defense Review, however, the DoD recognized the CCMRFs were not able to rapidly respond to an incident, leaving a gap between the state and federal response. To bridge this gap, the DoD reduced and reorganized the federal component of the CRE and increased the size of the National Guard component of the CRE by adding an additional echelon, the HRF. Shifting more of the force to the National Guard established a more regionally based approach [15] which improved rapid response and thus the life saving capability of the CRE. This new structure replaced the CCMRFs with the Defense CBNRE Response Force (DCRF) and two Command and Control Response elements (C2CRE) on the federal side, and established ten HRFs on the National Guard side. This change placed forces more geographically proximate to possible CBRN incident sites and provided more forces under the control of a sourcing state's governor, thereby

---

[2]Reserve status refers to personnel not assigned to their duties full-time but does not imply they are apart the US Army Reserve.

reducing the delay caused by the bureaucratic nuances of employing federal forces.

The exact command and control structure within the CRE is still evolving, but "the HRFs are supposed to establish a regional command and control structure to synchronize State Active Duty and Title 32 National Guard CBRN response forces including CERFPs and prepare for follow-on forces." [59] . Each HRF is expected to focus on planning, training, and exercising authority within its respective FEMA region to establish links between the local, state, and federal authorities. A majority of the HRF personnel, roughly 75%, are in a reserve status. Similar to a CERFP, units within the HRF are pre-existing and maintain a dual mission status (i.e. the HRF mission and the pre-existing mission). Finally, according to a Rand report published in 2010 [1] two HRFs will consist of units sourced from multiple states' National Guard units.

It is important to note that the establishment of CRE unit locations was not implemented based on a holistic analysis of the entire structure that exists today. The units were instituted and sited incrementally. While the DoD provided guidance and oversight of locations, it appears that stationing decisions were primarily left to the states' direction. According to a press release from 2001 referencing WMD-CST unit locations, "stationing decisions were made based upon criteria established by the Department of the Army and provided to the states. Criteria were designed to make the most of existing facilities and to ensure maximum coverage of the large metropolitan areas in each of the 10 Federal Emergency Management Agency regions" [6]. There does not appear to be any information in the open source regarding CERFP and HRF stationing, but it is likely that similar criteria were used. Delegating unit location decisions to each subordinate state may have created inefficiencies in the response capability of the CRE. The purpose of this thesis is to determine if these inefficiencies exist and if so, find cost efficient modifications that can improve the

coverage provided by the CRE.

2.3 Current CRE Strategic Guidance

There are several strategic documents that highlight the priority of CBRN consequence management within the homeland defense context. Below is a brief summary of these documents:

- **2012 Defense Strategic Guidance:** Developed at the behest of President Obama to review and update the DoDs strategy and shape the direction for the DoD over the next decade. Within this guidance, the President directed,"DoD will continue to develop joint doctrine and military response options to prevent and, if necessary, respond to mass atrocities" [13].

- **2014 Quadrennial Defense Review:** The Quadrennial Defense Review (QDR) is a report to Congress, mandated by law, which outlines the DoDs strategy and priorities. In the 2014 QDR, one of the three pillars for the DoD's defense strategy is to protect the homeland which specifically includes support to civil authority [42].

- **2013 Strategy for Homeland Defense and Defense Support to Civil Authorities:** The 2013 Strategy for Homeland Defense and Defense Support to Civil Authorities outlines the DoD's priorities and objectives for homeland defense. Two of the main objectives for the DoD included, "maintain preparedness for domestic Chemical, Biological, Radiological, Nuclear (CBRN) incidents and, develop plans and procedures to ensure Defense Support of Civil Authorities during complex catastrophes" [15]. The strategy also highlights an increased expectation from the public for a rapid and effective response to a catastrophic event from the federal government. It further recognizes the continued threat

posed by terrorists that seek to strike the United States using WMD. To protect the nation from such an attack, it stipulates the CRE be a modular force capable of providing both state and federal assets to respond to multiple CBRN attacks simultaneously. The strategy concludes by noting that while reduced budgets within the DoD have limited program expansions, investment in the CBRN consequence management enterprise must remain a top priority [15].

- **Chairman of the Joint Chiefs of Staff Instruction: Defense Response to Chemical, Biological, Radiological, and Nuclear (CBRN) Incidents in the Homeland: CJCSI 3125.01C:** This document outlines guidance from the Joint Chiefs of Staff for the DoD response to domestic CBRN incidents. Response is defined as "those actions necessary to save lives, protect property and the environment, and meet basic human needs after a CBRN incident has occurred" [11]. It directs the CBRN response to develop technical expertise and specialized equipment to effectively fill capability gaps that exist at the local and state level in response to a CBRN incident. The instructions also highlight the roles and responsibilities within the DoD for CBRN consequence management [11].

- **DoD Strategy for Countering Weapons of Mass Destruction:** This strategy primarily focuses on operations preventing an attack but does highlight the need for the DoD to provide rapid assessments of WMD attacks to facilitate future decisions [17].

2.4 CRE Doctrine

The current doctrine for the DoD's response to a CBRN incident is governed by *Joint Publication 3-41: Chemical, Biological, Radiological, and Nuclear Consequence*

Management [35]. This publication describes the context of the CRE in the US government's national response and provides an overview of the CRE at the strategic, operational, and tactical levels. The US government's national response is a three tiered approach (i.e., local, state, and federal levels) based on the National Incident Management System (NIMS) and National Response Framework (NRF). The basic premise of the strategy relies on an incident being handled by the lowest level until it becomes apparent that the current assets will become overwhelmed if left unsupported. The local response includes fire, law enforcement, and emergency medical services. WMD-CSTs can be utilized within this tier if pre-positioned to respond to an event but are normally considered a part of the state response. The state response is initiated when local responders are unable to effectively manage the incident and includes: state HAZMAT teams, state police units, state health department assets as well as the WMD-CSTs, CERFPs, and HRFs. The federal response is similarly initiated when state resources are overwhelmed and may include some of the following agencies: the Department of Energy radiation assessment teams, Federal Emergency Management Agency (FEMA) emergency response assets, or Joint Task Force Civil Support (JTF-CS) which manages the defense CBRN response force (DCRF) [55].

Developing an informative model for siting CRE unit locations requires an understanding of how the units are employed. A brief description of the National Guard CRE response is outlined below based off doctrine from Joint Publication 3-41.

At the onset of an incident, the closest WMD-CST would respond to detect and assess the impacts from a CBRN incident. A critical component of their assessment is to determine the scale of the incident, the number of resulting casualties, and the number of casualties in need of decontamination and medical treatment. This determines the extent of additional CBRN consequence management forces that are required. The assessment also "provides the necessary information to assist the in-

cident commander in determining upwind and crosswind points and best locations for search and extraction, decontamination, medical triage and emergency medical services, and other sites" [35]. The WMD-CST communicates their assessments to local authorities along with the National Guard Coordination Center (i.e., operation center responsible for coordinating CRE state assets outside the affected state) and USNORTHCOM, the combatant command responsible for the DCRF.

The next level of response comes from the CERFP. If the incident requires significant decontamination, search and extraction, or medical triage, the supporting CERFP for that state would arrive on scene within six hours of notification from the Governor of the owning state. The CERFP's initial deployment depends on the evacuation process. If the process is controlled, the CERFP will move to reinforce local responders at existing evacuation processing centers; otherwise they may need to establish additional evacuation centers. The CERFP's primary purpose is to "reinforce evacuation centers to increase capacity and throughput or establish search and extraction, decontamination, medical triage and emergency medical, expanding the geographic distribution of response capability" [35].

The final level of response, if needed, comes from the HRF. A HRF responds with additional search and extraction, medical treatment, and decontamination capabilities. It also provides a security element to assist with controlling traffic flow into and out of the incident site and a brigade headquarters to provide command and control of the state CRE forces.

Overall, the CRE assists by providing additional capability to local response efforts but also is "an important force multiplier by assisting with decontamination of local fire, police, and emergency medical services personnel and equipment, thus helping these immediate responders to stay safely engaged in the response" [35]. Figure 3 depicts the basic response to a CBRN incident.

Layered Response Spectrum

Legend

C2	command and control	JOC	joint operations center
C2CRE	command and control chemical, biological, radiological, and nuclear response element	JTF	joint task force
		LD/HD	low density/high demand
CERFP	chemical, biological, radiological, nuclear, and high-yield explosives enhanced response force package	NGCC	National Guard coordination center
		NGCE	National Guard command element
		NG JFHQ-State	National Guard joint force headquarters-state
DCRF	defense chemical, biological, radiological, and nuclear response force	USC	United States Code
DOD	Department of Defense	WMD-CST	weapons of mass destruction–civil support team
HRF	homeland response force		

Figure 3. Layered Response Spectrum [35]

At the tactical level, WMD-CSTs are governed by National Guard Regulation (NGR) 500-3 [55], and CERFPs are governed by National Guard Regulation 500-4 [54]. There is currently no individual doctrine for a HRF, but its basic requirements are outlined in Joint Publication 3-41. The doctrine guiding the CRE was developed as the force evolved and continues to be updated as assumptions are tested. This study

16

is only focused on the coverage a team can provide based on its geographic proximity to potential incident sites and, therefore the remaining discussion of doctrine will focus only on the required response times at each echelon of the CRE.

2.5   Doctrine: Response Time

Joint Publication 3-41 specifies response times for each of the units within the National Guard component of the CRE. WMD-CSTs are required to respond within three hours of notification, CERFPs within six hours of notification, and HRFs within six to twelve hours of notification. It is important to note that notification comes at the direction of the governor of the sourcing state and is not the same as the time the incident occurs. The time between the incident and notification largely depends on information available, communication flow, and the prerogative of the governor. The Joint Publication also describes WMD-CSTs as arriving in the vicinity of the incident site within the first six hours. It is not clear if this is a directive or presented to provide a basic expectation for local responders. Additionally, there is no discussion regarding the definition of vicinity. Outside of this description, there is not an explicitly stated requirement in doctrine for the arrival of a CRE unit to the scene to an incident.

We can find, however, a previously used proximity requirement for WMD-CSTs from a DoD commissioned study. The report, *Before Disaster Strikes: Imperatives for Enhancing Defense Support of Civil Authorities* [1], prepared for the Secretary of Defense in 2010, utilized a 250 mile coverage radius and five-hour response time (i.e., 250 miles assuming a 50 mph travel speed) to assess the coverage provided by the current stationing of WMD-CSTs. It is not clear how this maximum response time was derived, but NGR 500-4 does state WMD-CSTs assume a speed of 50 miles per hour when traveling to an incident site. Since this report was commissioned as a part of an advisory panel to the Secretary of Defense and members of Congress,

it is reasonable to assume the report's five hour response time for a WMD-CST is the current guidance within the DoD. We can extend this to conclude that a location is not covered by a WMD-CST if it is not located within five hours of a WMD-CST. Even though it is unclear how this response time was established and therefore may merit further analysis, to limit the scope of this research we will assume this requirement to be accurate. An equivalent study regarding CERFPs and HRFs does not exist. Therefore, the required response time for CERFPs and HRFs is estimated from their notification timelines.

Whereas the doctrine is somewhat ambiguous when defining required response times to the incident site, there is clearly a theme of rapid response throughout the guiding publications. Joint Publication 3-41 describes the WMD-CST missions as "rapid, and effective employment of reconnaissance capabilities... to provide assessments on the effects in terms of casualties and medical treatment (detect and monitor)" [35]. The arrival of additional forces is dependent on the assessment of the WMD-CST; a delay to the WMD-CST arrival will delay the response of the remainder of the CRE. Joint Publication 3-41 specifically states, "the initial assessments conducted by NG WMD-CSTs or other federal assessment teams are critical in providing DHS and other federal departments and agencies the necessary situational awareness to make quick decisions regarding resource sharing and coordination" [35]. As pointed out by Joint Publication 3-41, these decisions are critical to minimizing the impacts of a CBRN event and thus rapid response is directly tied to minimizing human suffering and saving lives.

The 2013 Strategy for Homeland Defense and Defense Support to Civil Authorities also highlights the important of rapid response, stating, "response elements have the highest probability to save lives within 72-96 hours after an incident" [15]. During this initial 72-96 hours, the amount of time CRE assets are able to support the

incident site is directly correlated to the overall impact the CRE has on mitigating the effects of the incident. The strategy goes on to state and succinctly summarizes the intent of this analysis, **"to address this time constraint, DoD will explore force-sourcing options that include a unit's proximity to the affected area"** [15]. The strategy continues, "Homeland defense and civil support missions require a rapid response, often measured in hours, not days" [15]. The National Preparedness Guidelines also emphasize rapid response, "...the ability to rapidly decontaminate large numbers of affected persons is critical in preventing injury or death" [12]. Finally, this notion of rapid response was the emphasis behind restructuring the CRE to leverage the more geographically dispersed National Guard.

Ensuring the National Guard component of the CRE can rapidly deploy is essential to meet the objectives outlined by the governing strategy and doctrine. Thus, the on-scene response time should be a significant requirement or, at the very least, should be clearly understood. Based on the requirement for rapid response, this thesis will argue that a location is only considered covered by a CRE element if it is within sufficient proximity to to guarantee rapid deployment. This study will analyze the current configuration of the CRE and how well it covers the population using this notion of rapid response. This study will make an assumption about the definition of rapid deployment based on current doctrine, but we also acknowledge there is additional analysis needed outside the scope of this thesis to better define a rapid response.

2.6 Previous Coverage Analysis

The current analysis on CRE coverage is limited, and most of the findings are presented without a description of the methodology. For example, in the previously discussed 2010 study, Abbot *et al.* [1] analyzed if the location and number of WMD-

CSTs was sufficient. A location was described as covered if it fell within a 250-mile coverage radius or a five hour response time of the closest WMD-CST. The study claimed all of the United States' most populated areas are adequately covered with some risks accepted in western Texas. Unfortunately, the authors did not disclose the exact methods of their analysis, and it is difficult to interpret their results. Some key questions arise about their modeling assumptions, such as: what is the threshold for being considered one of the United States' most populated areas, was the 250-mile distance calculated over road distance or straight line distance, and what defines adequate coverage. Moreover, their study also only addressed WMD-CSTs with no analysis of CERFPs or HRFs.

A second analysis of coverage is provided by the National Guard, which claims in its 2013 annual posture statement that 80 percent of the US population lives within 250 miles of CRE state response forces [14]. In their 2015 posture statement, they claim that 97% of Americans live within a five-hour response window of a National Guard HRF or CERP [18]. It is important, again, to note the National Guard is referencing a five-hour or 250-mile response window that was previously mentioned in the RAND report but not specifically addressed in doctrine. This 2015 posture statement also claims that WMD-CSTs can respond within 90-minutes of notification. All of these statements are presented to reassure the public of the CREs capabilities. As with the 2010 Abbot *et al.* [1] study, these claims are presented without providing the methodology for their analysis so they are difficult to verify. As written, these reports seem to highlight the best case components of the force which may unintentionally provide an overly optimistic view of the true capabilities. A rigorous analysis is needed to assess the validity of these claims and provide an assessment of the true coverage of the force.

2.7 Other CBRNE Response Enterprise Research

The remainder of the CRE research has occurred through Government Accountability Office (GAO) studies, advisory committees to senior DoD officials or members of Congress, and theses submitted in partial fulfillment of a masters of arts degree relating to the study of homeland security at DoD affiliated institutions. These reports were predominately conducted utilizing qualitative research methods and examine doctrine, training, and standards. Most also focus solely on one echelon of the CRE without examining the entire structure. We present this material to further highlight the importance of rapid response and, demonstrate the limited quantitative analysis previously conducted. Additionally, given the recent inclusion of the HRF, there is limited research that focuses on the entire CRE structure as it stands today.

2.8 Government Accountability Reports

The United States Government Accountability Office (GAO) provides oversight of federal programs by advising Congress on how effectively federal funds are being utilized. Their reports are supposed to be "objective, fact-based, nonpartisan, non-ideological, fair, and balanced" [4]. The GAO has conducted three studies related to the CRE: one in May of 2006 focused on WMD-CSTs [30], a second in 2009 focused on the DoD's federal CBRNE consequent management plans [32], and a third published in 2011 focused on CERFPs [59].

The 2006 GAO report [30] examined the WMD-CSTs' readiness to conduct missions in terms of training, equipment, and personnel on-hand as well as their administrative policies. The study found that, overall, WMD-CSTs were ready to assume their mission and any significant issues identified in this report were addressed prior to subsequent reports. The report also provided estimates for costs of establishing WMD-CSTs ($7.7 million) and annual operating costs ($3.4 million) that are useful

for development of model parameters in Chapter 4. There was, however, no quantitative analysis of coverage based on the WMD-CST array of forces.

The 2009 GAO report [32] focused on the DoD's plans and preparedness for CBRN consequence management. This report identified "DOD's ability to train and deploy forces in a timely manner to assist civil authorities to response to multiple CBRNE incidents is at risk" [32]. This report also highlighted a lacking defined requirement of the capability the DoD was expected to respond with to a CBRN incident. At the time of this report the CRE consisted of National Guard WMD-CSTs and CERFPS and three federal CCMRFS, a much larger federal component than currently exists today. The report highlighted the current structure of the CRE was found in internal DoD analyses to leave a significant amount of time between local responders capabilities being overwhelmed and federal assets arriving at the incident. It further identified a reduction of response time was needed to fill this gap. Although not specifically stated, it is likely these findings spurred the shift to a CRE structure more reliant on the National Guard to reduce response time.

Finally, the 2011 GAO report [59] studied the readiness level of CERFPS, how well they coordinate with potential incident partners, and their command and control framework. The study identified significant issues with personnel, training, and equipment. The biggest problem was maintaining the required number of specially trained personnel on hand to complete the mission. They also identified issues with guidance on coordination between CERFPs and incident partners. Finally, issues with the command and control structure were identified that mainly related to communications equipment, out of state agreements, and lack of exercises that practice command and control structure. The most pertinent finding related to the scope of this study was an issue with recall times, the time it takes to assemble the unit at its home location. A total of 13 of the 17 CERFPs surveyed in the study were not

conducting exercises to determine how long a no-notice recall of their forces would actually take, mainly because they felt such experiences would create tensions between employers and NG members and would adversely affect the unit. Without rehearsing this key component, a recall will likely take longer than anticipated, increasing the need for the unit's physical location to be as close as possible to the incident site to reduce response time [59].

2.9   Previous Theses

Each of the previously published theses examined a component of the CRE, predominantly the WMD-CST echelon. As stated before, all used qualitative research methods and primarily studied the force compared to existing doctrine. We first examine four theses focused on the WMD-CST echelon and then one focused on the HRF echelon.

2.10   WMD-CST

Early in the development of the response force, Besosa [24] analyzed the National Guard's role in responding to a Weapons of Mass Destruction attack in a research report conducted at the Air Command and Staff College. He identified the need for the development of doctrine to address WMD-CST certification process, expected capabilities, and employment. The study did not specifically analyze the coverage provided by WMD-CSTs but does highlight, "the states were selected after an objective analysis that places the teams closest to the greatest number of people, minimizes response time within a geographical area, and reduces the overlap with other teams' areas of responsibility" [24]. The source of this information comes from a DoD press release, but the methodology for the study was not presented.

In 2002 Erichsen [37] evaluated how well the established WMD-CST structure and

capabilities met the intent set forth in the initial DoD tiger team report, presidential directives, and the 1996 Defense Against Weapons of Mass Destruction Act. His methodology developed metrics from these initial guiding documents and analyzed the WMD-CST structure against previous and potential scenarios. It is important to note this study occurred before a large percentage of teams were in place; however, some of the issues identified still exist today. For example, the study highlighted the importance of WMD-CSTs rapid response utilizing a vignette from the Tokyo Subway Attack in 1995. Erichsen claims a similar Sarin gas attack could kill people within minutes and spread miles over a short time span. The failure of a WMD-CST team to rapidly detect this substance would lead to additional loss of lives. Erichsen also identified issues with the stationing of WMD-CSTs and their travel distance to potential incident sites. His analysis highlighted the large distance between the city of Miami, Florida's second largest city, and the closest WMD-CST. This distance has decreased since Florida added a second WMD-CST but, even today with two WMD-CSTs, the distance between Miami and the closest WMD-CST is still over 250 miles. Given Florida has two WMD-CSTs, traveling over 250 miles to the second largest city in the state appears sub-optimal. A quantitative analysis is needed to determine if modifications to the WMD-CST structure can improve coverage.

Brown [25] also studied WMD-CSTs in 2004 to determine if they were properly trained, equipped and structured to respond to a domestic CBRN incident. The study had little substance and did not specifically analyze response time or coverage. He did present the claim that the current structure covered 90% of the U.S. population, within a 250-mile radius, although no citation was provided for this claim.

In a more recent study published in 2013, Giles [41] studied the current structure of the WMD-CSTs versus a regional approach with one WMD-CST in each FEMA region. These two structures were subjectively evaluated against doctrine using six

key components: engaged partnership, tiered response, operational capabilities, unity of command, readiness to act, and cost. The author estimated operating costs for each WMD-CST based on annual personnel costs but did not include other costs such as training and maintenance. Using this cost metric, Giles concluded the cost of the larger structure is worth the value gained in the other key components. While Giles provided a solid overview of the capabilities of the WMD-CST, there is limited quantitative analysis of coverage other than identifying more teams provide better coverage. An analysis of the population covered by each force structure in relation to the cost would provide better insight.

2.11   HRFs

One of the few studies analyzing the HRFs and their capabilities was conducted in 2011 [61]. The study focused on recommending standards for the HRFs through a qualitative analysis using case studies of past CBRNE events and the Israeli CBRNE force. The study recommended providing each HRF with advanced technologies, establishing flexibility to respond to missions beyond CBRN events, and working closely with supported states. The study does not discuss unit locations or response time.

2.12   Call for Quantitative Analysis

In 2001 RAND conducted a study [48] to advise the Army on supporting the homeland security mission. The objectives of the report were to: (1) characterize the range of threats that need to be considered; (2) provide a methodology for homeland security; (3) delineate Army responsibilities; (4) describe additional force protection requirements that might be necessary; (5) evaluate capabilities, provide options, and highlight risks; (6) help the Army explain its role in homeland security.

This report recognized that the establishment of WMD-CSTs (and other newly developed organizations) had improved the nation's response capabilities, but there had been limited analysis that ensured the most cost-effective structure was implemented. The report argued that "more systematic...policy analyses that explore the performance and cost of alternative architectures of federal, state, and local actors" [48] are needed. The study also points out:

> "...system seems to have been constructed with little attention to cost and effectiveness and may have resulted in a system that has critical gaps (in responsiveness, for example, or capacity), effectiveness shortfalls, or unnecessary redundancies that only become apparent in an actual incident, and with potentially grave consequences. Far better to begin exercising this system and to undertake the necessary analysis to understand where, at the margin, investments and divestments should be made at the local, state, and federal levels." [48]

The report specifically called for analysis using simulation and optimization models to assist in understanding the optimal allocation of resources to minimize the consequences of various threats. Furthermore, it pointed to the Army's critical role in this process stating, "the Army should seize the initiative and take a leadership role in creating the necessary framework and supporting capabilities (databases, models, etc.) for homeland security studies and analyses" [48]. This thesis applies these ideas to improve the nation's ability to respond to a significant CBRN incident in a cost effective manner.

2.13 Facility Location Models

Currently, there is limited research focused on modeling optimal CRE unit locations. However, a similar problem, siting Emergency Response Services (ERS) such as police departments and fire stations, is well studied. Some recent research also

focuses on siting medical supply facilities for large scale emergencies. The following section reviews previous modeling techniques with similar applications that informs the development of the model in Chapter 3. We discuss the classification of facility location models, review classical approaches, demonstrate specific applications, and present previous solution techniques.

2.14 Facility Location Problem Taxonomy

We begin first with a brief overview of Daskin's [34] taxonomy of facility location problems:

- Topographic Characteristics: (1) Planar: Demands and facilities can occur anywhere on a plane, (2) Network: Demands and facilities can only occur on specified nodes and edges of a graph. (3) Discrete: Demands and facilities can only occur on a discrete number of nodes on a graph.

- Facilities to locate: (1) Exogenously specified: The number of facilities to be sited is dictated by influences outside the problem such as limited resources. (2) Endogenous specified: The number of facilities to be sited is a model output.

- Public vs. private: Private models often measure cost and benefits in monetary units. Public models often have goals that must be measured based on quality of service. These models must provide maximum coverage of its supported population while operating with limited resources and without completely ignoring a segment of the population.

- Capacitated vs. uncapacitated: The service capacity of the facility can be finite or infinite.

- Static vs. dynamic: Are the inputs always the same or will they change with time?

- Probabilistic vs. deterministic: Are the inputs known or do they occur with a certain probability?

- Single vs. multiple service: Do all the facilities provide the same type of service, are there different types of service required for each demand?

- Single objective vs. multi-objective: Does the model seek to optimize one objective or are there competing objectives that must be balanced?

- Desirable vs undesirable: Desirable models often seek to place facilities close to demands while undesirable models locate facilities as far from demands as possible. Locating trash dumps can be thought of as a undesirable facility location problem.

2.15 Classical Models

Often, the first step in facility location modeling is to define the objective function. Four commonly used objective functions include: minimize average travel distance (i.e., p-median problem), minimize the maximum distance to a customer (i.e., p-center problem), minimize the number of facilities needed to cover all demands for a given coverage radius (i.e., Set Covering Problem (SCP)), or maximize coverage of demands given a coverage radius and set number of facilities (i.e., Maximal Covering Location Problem (MCLP)). The following sections highlight these four different approaches and some of the extensions that have been developed to adapt the formulation more precisely to a given problem.

2.16 Set Covering Problem Approach

Siting emergency management facilities using a set covering problem (SCP) approach was first introduced by Toregas *et al.* [60]. The model seeks to find the

minimum number of facilities required to cover each demand node. "A demand point is treated as covered only if a facility, or a set of facilities, is available to provide the required service to the demand point within a required distance or time" [51]. Their initial model assumed the location of demand nodes and facility locations is finite, the given response time between any node and possible facility location is known, each facility has identical costs and a facility can be placed on a demand node. The SCP formulation is presented below:

Sets

- M: The set, indexed by i, of demand nodes.

- N: The set, indexed by j, of potential facility locations.

Decision Variables

- y_j: A binary decision variable equal to 1 if a facility is located at site j, 0 otherwise.

Parameters

- a_{ij}: A binary parameter equal to 1 if the distance from site i to facility j is within a specified coverage radius, 0 otherwise.

Formulation:

$$\text{Minimize} \sum_{j \in N} y_j \tag{2.1}$$

$$\text{s. t.} \sum_{j \in N} a_{ij} y_j \geq 1, \qquad \forall \, i \in M, \tag{2.2}$$

$$y_j \in \{0, 1\}, \qquad \forall \, j \, \in N. \tag{2.3}$$

29

The objective (2.1) minimizes the number of facilities that are sited. Constraint (2.2) requires every demand node be covered by at least one facility. Constraint (2.3) restricts the decision variables to binary values.

The model can be extended to address instances when facility location costs are not equal by adding a weight to each facility in the objective. The objective then becomes to minimize cost rather than the number of facilities.

Establishing the coverage radius is the most critical and difficult component of correctly formulating a SCP. The coverage radius can be defined in terms of distance or time, and it is normally determined using the input of subject matter experts and government regulations. The assumptions used to build the coverage radius determine the validity of the model.

Kolesar and Walker [47] demonstrated a use of the SCP approach as a part of their innovative model for relocating fire companies. In large urban cities when a large volume of fires occur, the coverage provided by available fire companies may be significantly reduced. To mitigate this effect, it is a common practice to relocate fire companies to cover vulnerable parts of the city. Due to the frequency of fires in New York City, coverage is constantly in flux and difficult to determine. Kolsear and Walker sought to develop an algorithm that would assist dispatchers in determining when and where coverage gaps existed and which available fire companies should move to cover these gaps. A key component Kolsear and Walker's work was ensuring the algorithm recommend simple adjustments by generating the minimal moves necessary to restore coverage. To accomplish this, the authors formulated and solved a SCP model. Empty fire houses were the facility locations, and the uncovered neighborhoods were demand nodes [47]. Using the SCP approach, the algorithm found the minimum number of fire companies needed to cover all the uncovered demand nodes. The next stage restricted relocations to this number and then assigned the spe-

cific companies by minimizing travel distance such that currently covered demands remained covered. The complete algorithm was compared to the current system through a simulation which replicated one of the worst nights in terms of number of fires, in the Bronx. In total the Bronx received 288 alarm calls, double the normal amount for a day. The authors' algorithm achieved a 10% increase in coverage of neighborhoods compared to the relocation system that was used that night. As a result, New York City fully implemented the authors' algorithm into their dispatching process.

While the SCP approach is useful, it covers individual demands regardless of their size or location [45]. Small, remote demands may disproportionally contribute to the resources required to cover all demands and lead to solutions that exceed resource limitations. For these instances, use of the SCP approach requires solving the problem multiple times with differing coverage radii. This is done to highlight the trade-off between cost and service provided.

2.17   MCLP Approach

To address situations when the SCP approach resulted in solutions that exceeded resource limitations, Revelle and Church [27] developed the Maximal Covering Location Problem (MCLP). The MCLP seeks to maximize coverage of a population within a defined coverage radius given a set number of facilities [27]. This formulation unlike the SCP takes into account the size and location of demands. Schilling *et al.* [58] points out, that demand is required to be covered under the SCP, while coverage is optimized under the MCLP. The MCLP approach, however, can leave demand nodes uncovered. The MCLP formulation utilizes the same sets, decision variables and parameters as introduced in the previous formulation along with the following decision variables and parameters:

Decision Variables:

- z_i: A binary decision variable equal to 1 if a demand node i is covered by at least one facility, 0 otherwise.

Parameters:

- h_i: The amount of demand at demand node i.

- d_{ij}: The distance from demand node i to facility j.

- r: The coverage radius.

- a_{ij}: A binary parameter equal to 1 if $d_{ij} \leq r$, 0 otherwise.

- p: The number of facilities to be sited.

Formulation:

$$\text{Maximize} \sum_{i \in M} h_i z_i \tag{2.4}$$

$$\text{s. t.} \sum_{j \in N} a_{ij} y_j \geq z_i, \qquad \forall\, i \in M, \tag{2.5}$$

$$\sum_{j \in N} y_j = p, \tag{2.6}$$

$$y_j \in \{0, 1\}, \qquad \forall\, j \in N, \tag{2.7}$$

$$z_i \in \{0, 1\}, \qquad \forall\, i \in M. \tag{2.8}$$

The objective (2.4) maximizes the population covered within the specified coverage radius. The first set of constraints (2.5) require at least one facility to be within the coverage radius for the coverage decision variable z_i to be set to 1. Constraint (2.6) defines the number of facilities to be sited. The final constraints (2.7) and (2.8) restrict the decision variables to binary values.

The general form of the MCLP assumes that coverage is binary, i.e., a demand is covered or not. Similar to the SCP, defining the coverage radius is a critical component affecting the result. In the public sector, determining the number of facilities to site is often dictated by the available resources. The MCLP can also be solved recursively with different coverage radii and facilities to examine trade-offs of cost, coverage, and service quality. Some of the problem's applications and extensions are discussed in the following paragraphs.

An extension of the MCLP developed by Daskin [33] is the Maximum Expected Covering Location Problem (MECLP). The motivation for this extension was derived from ambulance dispatching, where the closest ambulance may be on a call and not available. This model's objective function first seeks to minimize the number of facilities sited and subsequently seeks to maximize dual coverage of demands. To model this approach, the authors assumed that each facility has an identical and independent probability p of being unavailable. For larger values of p, the best solution resulted in locating all facilities at the node with the greatest demand. Gendreau *et al.* [40] developed a similar double coverage model for ambulances wherein the objective seeks to maximize the number of demand that is covered twice but does not include the probability of coverage availability as apart of the model.

Another extension addresses the assumption of all-or-nothing coverage of the MCLP. In the general form of the MCLP, a demand node is either covered or not. Berman and Krass [23] identified that this all-or-nothing approach may not fully capture the true coverage provided by a facility. For example, consider a demand node that exists one mile outside a coverage radius. While the optimal response time may not have been achieved, the difference in response between this node and a covered node can be minimal. This gradual change in coverage, however, is not captured utilizing the classic MCLP Approach. The authors developed the generalized maximal

covering location problem (GMCLP) "to provide a significant increase in modeling flexibility beyond the standard MCLP" [22]. The coverage of a demand node is captured using a decreasing step function of the distance of the demand node to the closest facility. This change in the definition of coverage allows for a more detailed representation of coverage.

Pirkull and Schilling [56] also implement the idea of partial coverage into a capacitated MCLP model. They defined the model as the maximal covering location problem with capacities on total workload [56]. They argued that, when siting capacitated facilities utilizing the MCLP approach, the demand nodes left uncovered would still utilize facilities and contribute to the load placed on a facility. Without a partial coverage function uncovered demands were arbitrarily assigned to facilities with available capacity. This is likely not a practical solution since a demand will generally be serviced by the closest facility. For example, consider an individual that lives outside the coverage radius needs medical care. They are most likely to utilize the closest hospital. Implementing a partial coverage function, facilities were sited such that uncovered demands were still accounted against a facility's available capacity. This resulted in more accurately accounting for the impact of uncovered demand on a facility's capacity.

2.18 p-median Approach

The p-median approach was first developed by Hakimi [43]. This model seeks to minimize the average distance traveled from a demand node to a facility over the entire network by locating p facilities. Klose and Drexel [46] refer to this problem as the minsum problem, as the objective seeks to minimize the sum of the distances from each demand node to its closest facility. Berman [22] defines it as "the best travel distance for an average customer". The p-median formulation utilizes previ-

ously introduced sets, decision variables, and parameters and is augmented with the following additional decision variable:

Decision variables:

- x_{ij} : A binary decision variable equal to 1 if demand i is assigned to facility j, 0 otherwise.

Formulation:

$$\min \sum_{i \in M} \sum_{j \in N} d_{ij} x_{ij} \tag{2.9}$$

$$\text{s. t.} \sum_{j \in N} x_{ij} = 1, \qquad \forall\, i \in M, \tag{2.10}$$

$$x_{ij} \leq y_j, \qquad \forall\, i \in M,\ j \in N, \tag{2.11}$$

$$\sum_{j \in N} y_j = p, \tag{2.12}$$

$$x_{ij} \in \{0, 1\}, \qquad \forall\, i \in M,\ j \in N, \tag{2.13}$$

$$y_j \in \{0, 1\}, \qquad \forall\, j \in N. \tag{2.14}$$

The objective function (2.9) seeks to minimize the total distance of each unit to the closest facility. Constraint (2.10) requires each unit be assigned to one facility. Constraint (2.11) requires a facility to be located at site j if a demand is assigned to site j. Constraint (2.12) restricts the number of facilities to equal p. Finally, Constraints (2.13) and (2.14) are the binary restrictions.

The Army National Guard implemented the p-median approach as apart of their mobile simulator implementation plan [52]. The objective of the plan was to minimize the total travel distance for a set of mobile trainers. The authors utilized a decomposition strategy, where the problem was broken down into stages and solved with different models at each stage. The output from the previous model served as the

input to the next model. The first stage of the process utilized a p-median approach to select the home base for each mobile trainer. Demands were defined as unit locations in need of training and facilities were defined as potential home base locations for the mobile trainers. Distances were weighted by the number of platoons at each location that needed training. The result of this step found home base locations that minimized the travel distance for the mobile trainers. The result of the full model reduced the expected travel distance of the mobile trainers by 72,850 miles, which requires about 70% fewer miles than the initial plan. The reduced travel resulted in an estimated savings of over $8.6 million dollars a year or $123 million over the 20 year life of the system.

2.19 p-center Approach

The public sector commonly defines coverage of a population by the demand with the lowest level of service. This type of coverage can be modeled using a p-center approach, wherein the objective is to site p facilities that minimize the maximum distance between a demand node and its closest facility. Klose and Drexel [46] define this problem as a minmax problem since it seeks to minimize the maximum distance. Finally, Berman [22] defines this approach as seeking to "optimize the travel distance for the worst covered customer". The p-center formulation utilizes previously introduced sets, decision variables, and parameters and is augmented with the following additional decision variables [46]:

Decision Variables:

- r: The maximum distance between a demand node and the closest facility.

- z_{ij}: A binary decision variable equal to 1 if demand node i is covered by facility j, 0 otherwise.

Formulation

$$\text{Minimize } r \tag{2.15}$$

$$\text{s.t.} \quad r - \sum_{j \in N} d_{ij} z_{ij} \geq 0, \qquad\qquad \forall\, i \in M, \tag{2.16}$$

$$\sum_{j \in N} z_{ij} = 1, \qquad\qquad \forall\, i \in M, \tag{2.17}$$

$$z_{ij} - y_j \leq 0, \qquad\qquad \forall\, i \in M,\ j \in N, \tag{2.18}$$

$$\sum_{j \in N} y_j = p, \tag{2.19}$$

$$z_{ij} \in \{0,1\}, \qquad\qquad \forall\, i \in M,\ j \in N, \tag{2.20}$$

$$y_j \in \{0,1\}, \qquad\qquad \forall\, j \in N. \tag{2.21}$$

The objective function (2.15) minimizes the maximum distance between a demand and the closest facility. The first set of constraints (2.16) bound the value of r. The second set of constraints (2.17) establish the facility that covers each demand. Constraints (2.18) ensure that if a demand is covered by a facility at site j, a facility exists at that location. The fourth set of constraints (2.19) set the number of facilities to be sited. Finally, constraints (2.20) and (2.21) are the binary constraints.

2.20 Conditional Covering Problem

Moon and Chaudhry [50] introduced the conditional covering problem (CCP) as a variant of the unweighted SCP. The CCP has the same objective as the SCP –to establish the minimum number of facilities to cover all demands– but adds an additional constraint requiring each sited facility be covered by another facility. The CCP formulation utilizes previously introduced sets, decision variables, and parameters and is augmented with the following additional parameter:

Parameters:

- b_{jk}: A binary parameter equal to 1 if facility j is covered by facility k, 0 otherwise, $b_{kk} = 0$.

Formulation

$$\text{Minimize} \sum_{j \in N} y_j \tag{2.22}$$

$$\text{Subject to:} \sum_{j \in N} a_{ij} y_j \geq 1, \qquad \forall i \in M, \tag{2.23}$$

$$\sum_{k \in N} b_{jk} y_k \geq y_j, \qquad \forall j \in M, \tag{2.24}$$

$$y_j \in \{0, 1\}, \qquad \forall j \in N. \tag{2.25}$$

The objective (2.22) sites the minimum number of facilities. The first set of constraints (2.23) require every demand be covered by a facility. The second set of constraints (2.24) require every facility be covered by another facility. The final constraint (2.25) restricts the decision variable to binary values.

The CCP has few previous applications but, Lunday [49] introduced a special case of the CCP, the modified covering problem (MCP), that specifically applies to siting WMD-CST units. In the MCP, each facility has the same coverage radius, facility costs are identical, facility locations are the same as the set of demand nodes, and a facility cannot cover a co-located demand. Since WMD-CSTs are identical units, assuming equal costs and coverage radius are reasonable assumptions. The final constraint is included because "a terrorist biological or chemical attack on a city may render its own team incapable of performing its mission" [49]. Preventing a facility from covering a colocated demand identifies the coverage provided in a worst case scenario.

The MCP is introduced with an identical formulation to the CCP model and the

author then demonstrated that constraint (2.23) and constraint (2.24) can be satisfied with the constraint below:

$$\sum_{j \in N} a_{ij} y_j \geq 1, \qquad \qquad \forall \, i \in N, \ (a_{jj} = 0). \qquad (2.26)$$

Constraint (2.26) still requires every demand node be covered, but, by setting the diagonal of the A matrix to 0, a facility cannot cover itself. Since every located facility exists on a demand node, each facility must be covered by another facility. This formulation is well suited for our problem statement, and a variant of this model is developed in Chapter 3.

2.21 Large Scale Emergencies

Jia *et al.* [45] developed models specifically designed for siting facilities that would support a large scale emergency. They define large-scale emergencies as "those rare events that overwhelm local emergency responders and require regional and/or national assistance, such as natural disasters and terrorist attacks" [45]. They proceed to highlight that large scale emergencies are unique in their low frequency and catastrophic effect on the population.

> "The tremendous magnitude and low frequency of large-scale emergencies require a modification in the definition of facility coverage to allow for redundant facility placements and tiered facility services to ensure an acceptable form of coverage of all demand areas when a large-scale emergency occurs." [45]

Their application focused on proactively locating medical stockpiles and reactively siting distribution centers that would distribute medical supplies after a large scale

emergency. Their model considered the number of facilities each demand point will require and the service quality of each facility based on the distance a facility is located from a supported demand node. The proactive facility location model, which shares the most in common with CRE siting, involves deciding where to site the facilities and the amount of supplies to stockpile at each location. They develop three objective functions for different types of large scale emergencies while acknowledging that any solution will still involve the loss of life. Because of this, Jia *et al.* emphasize "care should be taken in prioritizing one solution over another" [45].

The model developed for proactive purposes uses an approach similar to the MCLP with a slight change in the objective function. Instead of just weighting each demand by population, they weight each demand based on the likelihood that a demand point will suffer a large scale emergency of a particular type, the impact of that scenario on the demand point, and the population at that demand. A demand with a high probability of experiencing a scenario with a large potential impact and a large population will be weighted highly, increasing the value to the objective function attained by covering that node. Additionally, since there are different likelihoods and effects for each scenario, there is potentially a different optimal solution for each scenario. To find a global optimal solution they find the solution that minimizes the sum of the difference of each scenario's objective from its respective optimal solution. The authors found their model improved dual coverage of demands over classical models. Dual coverage is important in large scale emergencies because of the potential for a facility to be destroyed during the emergency.

The authors also consider a *p*-median and *p*-center approach for reactive models. Reactive models are designed to site distribution facilities after a large scale emergency has occurred. The authors use this approach "based on the idea that the accessibility and effectiveness of an EMS facility in response to an emergency situation will increase

if the distance from the facility to the demand points decreases" [45]. The reactive model is less related to the CRE model since CRE units must be sited prior to an attack. It could, however, be useful for planning potential decontamination or triage points for CRE units after arriving at an incident.

Murali *et al.* [51] also examined facility location for large scale emergencies. They noted, "an important additional consideration when planning a response to a large-scale emergency is that there is a large degree of uncertainty associated with the location of the emergency and the number of people affected" [51]. They used an MCLP extension as well to formulate a model for their problem. They adapted Berman's ideas from the GMCLP, where coverage is not binary but a decreasing step function of the distance. The authors' argued "the further away the facility is, the smaller the fraction of the demand it can cover." [51]. They also highlighted that it is difficult to determine which medical facility a person will be able to utilize during an event due to unknowns such as road damage. However, the authors argued the likelihood of using a facility decreases as the distance increases. Thus, the further away the facility is located from a demand, the less likely it will cover it. The "objective is to maximize the percentage of the affected population that successfully receives medication" [51]. The model also allows for demand to be split across multiple facilities that may provide different coverage levels.

2.22 Multi-Objective Optimization

Real world problems are often comprised of multiple objectives that are negatively correlated with each other; improving one objective is accomplished at the expense of the other. As the facility location discipline has grown there is a recognition that many facility location problems have multiple objectives [29]. The most common of these problems balance maximizing capability while minimizing cost. While a multi-

objective problem can be modeled using a single objective, Current [29] noted the advantage of providing "the decision maker with a range of non-inferior siting configurations which demonstrate the inherent trade offs among the conflicting objectives". This set of solutions allows a decision maker to understand the range of alternatives [28] and balance the trade-offs by applying their judgment and experience to select an 'optimal solution' [29].

Within the context of the CRE, the competing objectives are to maximize coverage while operating with a limited budget. Below we highlight some useful applications that inform the model in Chapter 3.

A study of the Denver fire department was conducted by Plane *et al.* [57] in order to maintain coverage while reducing costs. The key components of the study involved how to quantify coverage, measure the current level of coverage, develop a model that held the current level of coverage while minimizing cost, validate assumptions with inputs from the firefighters and city officials, and consider political factors that may impact the solution's implementation. The authors formulated the problem as an SCP using a hierarchical objective function. Their hierarchical approach worked by first finding the minimum number of fire stations needed given a certain coverage criteria. Coverage was determined based on response time since previous studies demonstrated a positive correlation of response time and minimizing fire damage. The approach subsequently maximized the number of existing fire stations, while keeping the total number of fire stations equal to the solution found in the first step. This approach is used to consider the economic and political costs of moving an existing fire station.

The authors encountered issues when the model pushed most of the fire stations to boundaries of the city and failed to place enough coverage in the downtown area. To account for this, they used the fire chief's experience in siting the downtown stations and held the downtown area locations as fixed. The authors resolved the problem

and were again provided feedback by the firefighters regarding issues in the solution. More adjustments to the model were made, and eventually a solution was found that satisfied the firefighters and city officials. The study resulted in a savings of \$2.6 million over six years and an annual savings of \$1.2 million based on 1974 wages.

Daskin [34] introduced a similar model that locates facilities to achieve a coverage level while maximizing the number of existing facilities that are a part of the solution. His model is applicable to siting the CRE since the response enterprise is already sited at existing locations. If the current configuration is not optimal, maximizing the use of existing facilities will reduce the cost of adjusting the location of these units. Additionally, "closing a [facility] that has served as a focus of community activity and that provides a sense of security to residents may be difficult" [20]. A model that does not drastically change the existing enterprise configuration is more likely to be used by a decision maker.

Badri *et al.* [20] also developed a multi-objective model for locating fire stations in support of the city of Dubai. This model assumed, "optimizing the location of fire departments includes minimizing the sum of losses from fire and the cost of providing the service" [20]. The authors, however, acknowledged that an implementable solution must also satisfy a number of other criteria. To find an optimal solution that balances the many competing objectives, a multi-objective goal programming model is developed. In preemptive goal programming, the objectives are ranked and solved sequentially. Each objective is achieved to the greatest extent possible while maintaining the previous objective. Ideally, these goals are ranked by the decision maker. The authors provided the following rationale for using goal programming:

> "...the decision to locate a fire station involves more than one government agency. Each of these agencies has certain goals in mind that must be satisfied. To add to the complexity of the situation, several decision-makers from these agencies are present with different levels of authority.

For example, those from the Civil Defense have more authority than their counterparts from the municipality. In other words, the priority attached to each of the goals is influenced by the type of government agency involved as well as the position of the decision-maker within his own agency. Given all these circumstances, goal programming could be the only technique suitable."

The authors presented a model that incorporates eleven strategic objectives. Several of their objectives include: (1) minimizing fixed costs and annual operating costs, (2) maximizing service to those area that require it most, (3) minimizing average and maximum distance from demand sites to the station, (4) minimizing average and maximum time traveled, (5) siting the minimum number of fire stations, and (6) siting stations with minimum service overlap. Certain areas of the city where considered more important based on an increased potential monetary loss from a fire. Minimizing the maximum distance is added to the model as a worst case scenario. The average distance from a station to a sub-area is used for normal conditions. Maximum time to a sub-area is used to reflect road conditions and congestion. The authors also introduced an idea of *favored area status* that could represent existing stations that need to stay open. They also attempted to locate fire station along boundaries with low fire rates.

The authors first formulated the problem as a set covering problem and analyzed the number of fire stations needed for various maximum response times. This information was then used in their preemptive goal programming model which they solved with multiple times varying the order priorities. The results of this analysis were presented to the stakeholders to analyze the trade-offs amongst the different priorities and costs.

2.23   Multiple-Service Model

Belardo *et al.* [21] present a model quite different from the models previously analyzed along with a much different application. Their model is framed around siting response resources for a major maritime oil spill. Oil spills can have a dramatic impact on the environment and economy of an affected region, and strategically siting resources that assist in mitigating the impacts of the oil spill is critical. They identified several requirements for siting these resources. First, there are characteristics of a spill that affect the type of required response that are independent of location. For example, different types of oil require different types of equipment to clean. Thus coverage requirements are dependent on being covered by multiple capabilities. They also identified that spill probabilities vary by location much the way the probability of a CBRN event is location dependent. Predicting the probability of an oil spill is extremely difficult given how infrequently they occur. To address this issue, they use conditional probabilities that are easier to estimate. For example, given a spill occurred, what is the probability it occurred in a certain city? A similar methodology could be used to estimate the likelihood of a CBRN event taking place in different cities. In this article, the conditional probability associated with each city is determined by the volume of oil transferred and the number of ships traversing through the region. Finally, their model considers different factors such as economic and environmental impact. They solved the problem multiple times, trying to minimize with respect to each consideration. The multiple solutions were then presented to the decision maker, which allowed them to make the decision based on how they prioritized the considerations [21].

Moore and Revelle [38] define a nested hierarchical maximal covering problem. The objective of this model is to maximize coverage given constraints on the number and type of facility locations or total investments in all facility types. The model al-

lows for different coverage distances for each type of facility and different requirements on what defines a node as covered.

2.24 Formulation

As demonstrated by Jia [45] a p-center, p-median, and covering model all can be implemented for modeling the response to a large-scale emergency. For the models developed in Chapter 3, we implement extensions of the MCLP and SCP. p-median and p-center approaches are more applicable to siting facilities that have a much more frequent demand. Since CBRN events are much more infrequent, small gains in response time have less impact on coverage. Additionally, these approaches do not capture the increased importance of cities with larger populations since they are more likely to be attacked. A more useful approach is to maximize the population covered within a desired response time using a MCLP approach. To balance the trade-off of cost and coverage, we will develop a set of non-inferior solutions that identify the range of alternatives to a decision maker. Additionally, we can identify the required number of units at each echelon needed to achieve full coverage using a SCP approach. These models will be further developed in Chapter 3.

2.25 Floyd's Algorithm

Coverage in Chapter 3 and 4 will be based on the distance between a CRE unit and a demand. It is important this distance represents the shortest path between these two nodes. Given a connected network we can find the shortest path between any two nodes in a network using Floyd's Algorithm [39]. Floyd's algorithm guarantees finding the shortest path between all pairs of nodes on a network but does not detail the route used for the shortest path. The algorithm is detailed as follows:

Data: input Distance Matrix D with n nodes

for $k = 1$ to n **do**

   for $i= 1$ to n **do**

      for $j=1$ to n **do**

         $D(i,j) = min(D(i,j), D(i,k) + D(k,j));$

      end

   end

end

Result: Output D which contains the shortest path from any node i to any node j.

Algorithm 1: Floyd's Algorithm

This algorithm is implemented in Chapter 4 to find the shortest path between each county in the Continental United States.

III. Methodology

3.1 Introduction

This chapter develops the methodology for analyzing the impact CRE unit locations have on rapid response. We review the objective, approaches, modeling assumptions, model formulations, and discuss the use of existing data to develop model parameters.

3.2 Scope

The purpose of this analysis is to provide insight into CRE unit locations. We first will evaluate the current structure and then identify alternative structures that may improve the response capability of the CRE. We focus specifically on structures that maximize coverage provided by the initial response of WMD-CSTs, CERFPs, and HRFs while minimizing change to the current structure. Initial response constitutes the closest team at each echelon that would respond to a CBRN incident. Follow-on response is not modeled because of the additional time available to respond and the possible use of air assets, both of which largely negate the importance of unit location. Finally, the WMD-CST response is treated as the most critical of the three echelons since an assessment from a WMD-CST will dictate whether additional assets are required. For this reason WMD-CSTs are analyzed both separately and as a part of the whole CRE structure.

3.3 Approach

We develop a multi-objective multi-service extension of the MCLP which seeks to maximize coverage of the population within a defined coverage radius while minimizing the cost of modifications. The multi-service component of the problem requires a

demand to be covered by each echelon of the CRE, a WMD-CST, CERFP, and HRF. To account for multi-objective nature of this problem we develop a set of non-inferior solutions using the ϵ-constraint method. This method involves iterating the bound on the number of relocations allowed and maximizing coverage at each iteration. By iterating from 0 relocations to the existing number of teams we develop the entire range of alternatives. This provides insight into the trade-off between coverage and cost of CRE structure modifications. We also develop a SCP Model to find the minimum number of facilities needed to cover the entire population given a specified coverage radius. This is utilized to assess how many additional units are need to attain full coverage given an existing structure.

3.4 Model Assumptions

Both models share common assumptions that fall into two main categories: (1) assumptions the translate the real world system to a mathematical model and (2) assumptions about the future of the CRE structure.

First, we limit the possible facility locations and demands to a finite set of nodes on a network. These nodes represent population centers for each county in the continental United States. Limiting the solution space reduces the complexity of the problem and frames the model around the existing US road network. Open source data from government agencies provides a realistic indication of distances between all nodes. Furthermore, we assume to know the time it takes to traverse between nodes in the network based on the road distance and an assumed rate of travel and that the rate of travel is deterministic.

Next, we assume that the probability of a CBRN incident occurring at a given location is positively correlated with the location's respective population. Thus a greater demand is generated at a more populated node. Resource limitations prevent

49

establishing enough units to provide full coverage, and therefore coverage is prioritized by the level of demand. Given the importance of rapid response, coverage is considered binary and a demand must be within a specified distance of a unit to be considered covered.

Given the scope of destruction that can occur in a CBRN attack, it is possible a demand will neutralize a CRE unit's capabilities. Thus, in a pessimistic scenario, we assume a unit located within a certain radius of a CBRN incident will be unable to effectively respond to that incident. Coverage of the incident site will be determined by the closest unit located outside of this radius. To highlight this risk associated with a pessimistic scenario we introduce a minimum standoff distance that a unit must be from a demand to provide coverage. We also assume the population size at the demand is positively correlated with the risk to a CRE unit. Thus, a greater population at a CRE unit's location correlates to an increased probability of a CRBN event neutralizing a CRE unit's capabilities. In Chapter 4 the population colocated with CRE units is used as a measure of risk for the entire CRE structure. Finally, we assume that the probability of multiple simultaneous or near-simultaneous CBRN events is low and will present infrequent demand. Thus, we model the facilities as uncapacitated.

The remaining assumptions relate to the CRE structure. First, the effectiveness of each WMD-CST, CERFP, and HRF is assumed to be identical and sufficient. Next, we restrict the number of WMD-CSTs, HRFs, and CERFPs to the current number in the existing enterprise. Furthermore, it is assumed each state will continue to host at least one WMD-CST. This is based on the presumed political cost of removing an existing capability from a state. For example, in 2013 the DoD proposed disestablishing the 24th WMD-CST located in New York and 48th WMD-CST located in Florida. A number of Senators and Congressman from both states including House

50

Appropriations Defense Subcommittee Chairman Congressman Bill Young (FL), Sub-committee Member Congressman Bill Owens (NY), and Congressman Michael Grimm (NY) fought the proposal and were able to convince the Secretary of Defense Chuck Hagel to reverse the decision [2] [3].

The formulation of this problem also assumes that a WMD-CST can cover a location outside the state in which it is located. Many states have inter-state agreements already established to share CBRN resources. Additionally, WMD-CSTs can be used to support other states via coordination through the National Guard Bureau, or they can be federalized to respond to an attack anywhere in the United States if approved by the appropriate authority. The importance of this assumption is demonstrated in Chapter 4.

We also assume that a state will not host both a HRF and a CERFP. Most states are facing challenges meeting the minimum manning requirements for the existing CERFPs. Fielding a HRF in addition to a CERFP would only exacerbate a state's personnel challenges [31]. Additionally, funding training events or activations for real world incidents for both of these units would significantly strain a state's fiscal resources. There must be a roughly equitable allocation of resources from each state to the combined HRF and CERFP-levels of the CRE across the states.

Given these assumptions we now present the formulation of our model.

3.5 MCLP Model

Our model adopts an MCLP objective where it seeks to cover the maximum number of people within a rapid response window given a fixed number of WMD-CSTs, CERFPS, and HRFs. In order for a demand to be considered covered it must be located within a maximum distance of at least one team at each echelon. Additionally, to account for the risk of being collocated with an incident, a team

will have a minimum stand-off distance it needs to be from a demand to provide coverage, similar to the MCP. The MCLP model will be applied with and without the minimum stand-off distance in Chapter 4 to highlight risk in a pessimistic scenario and demonstrate the necessity to incorporate this concept into future planning. Finally, to minimize the change to the current structure, we introduce a constraint that bounds the number of relocations that can occur. When no relocations are allowed, the model returns the coverage provided by the current structure. When the maximum number of relocations are allowed, the solution returned is unaffected by the current structure. Since Washington D.C. only has one location in this network and each state must have one WMD-CST, the maximum number of relocations for WMD-CSTs is one less than the total number of teams. Solving the model with the number of allowable relocations increasing from 0 to the total number of teams produces a set of non-inferior solutions that will demonstrate the trade-off between coverage and cost. The sets, decision variables, parameters, and formulation for our model are presented below:

3.5.1 Sets.

- $G = (N, A)$: The underlying network.

- N : Set of nodes (indexed by j) in the network that represent possible facility locations and demands.

- A : Set of undirected arcs (i, j) in the network, $i, j \in N, i \neq j$.

- D : Set of demand nodes (indexed by i) in the network, $D \subseteq N$.

- S : Set of states $s = 1, ..., 49$, representing the 48 continental states and Washington D.C..

- $N_s \subset N$ Set of nodes located in state s, $s \in S$.

- R : Set of FEMA regions $r = 1, ..., 10$.

- $F_r \subset N$ Set of nodes located in FEMA region r, $r \in R$.

- $L = \{w, c, h\}$: The set of CRE echelons indexed by ℓ, where the indices correspond to the WMD-CST, CERFP, and HRF echelons, respectively.

3.5.2 Decision Variables.

This model contains two linked decisions: where to site facilities at each echelon and which demands to cover.

- y_j^ℓ : A binary decision variable equal to 1 if a facility at echelon level ℓ is located at site j, 0 otherwise, $\forall\ \ell \in L,\ j \in N$.

- z_i : A binary decision variable equal to 1 if demand at node i is covered by a facility at each echelon level, 0 otherwise, $\forall\ i \in D$.

3.5.3 Parameters.

- h_i : Demand associated with node i, $\forall\ i \in D$.

- d_{ij} : Distance from demand node i to facility j, $\forall\ i \in D,\ j \in N$.

- r_{min}^ℓ : Minimum stand-off distance at echelon ℓ.

- r_{max}^ℓ : Maximum coverage radius at echelon ℓ.

- a_{ij}^ℓ : A binary parameter equal to 1 if $r_{min}^\ell \leq d_{ij} \leq r_{max}^\ell$, 0 otherwise, $\forall\ j \in N$, $i \in D$.

- ψ_j^ℓ : A binary parameter equal to 1 if a facility at echelon level ℓ currently exists at site j, 0 otherwise $\forall\ j \in N$.

- p^ℓ : The number of facilities at echelon ℓ, that must be sited, $\forall\, \ell \in L$.

- q^ℓ : The minimum number of current unit locations at echelon ℓ that must be maintained, $\forall\, \ell \in L$.

3.5.4 Model Formulation.

$$\max \quad \sum_{i \in D} h_i z_i \tag{3.1}$$

$$\text{subject to} \quad \sum_{j \in N} a_{ij}^\ell y_j^\ell \geq z_i, \qquad\qquad \forall\, \ell \in L, \;\; i \in D, \tag{3.2}$$

$$\sum_{j \in N_s} y_j^w \geq 1, \qquad\qquad \forall\, s \in S, \tag{3.3}$$

$$\sum_{j \in N_s} y_j^c + \sum_{j \in N_s} y_j^h \leq 1, \qquad\qquad \forall\, s \in S, \tag{3.4}$$

$$\sum_{j \in F_r} y_j^h \leq 1, \qquad\qquad \forall\, r \in R, \tag{3.5}$$

$$\sum_{j \in N} y_j^\ell = p^\ell, \qquad\qquad \forall\, \ell \in L, \tag{3.6}$$

$$\sum_{j \in N} \psi_j^\ell y_j^\ell \geq q^\ell, \qquad\qquad \forall\, \ell \in L, \tag{3.7}$$

$$y_j^\ell, \in \{0, 1\}, \qquad\qquad \forall\, \ell \in L, \; j \in N, \tag{3.8}$$

$$z_i \in \{0, 1\}, \qquad\qquad \forall\, i \in D. \tag{3.9}$$

The objective function (3.1) seeks to maximize the total demand covered. The decision variable z_i is bounded by Constraint (3.2) and only equals 1, meaning demand i is covered, if at least one facility (i.e., among y_j^ℓ, $\forall\, j \in N$) at each echelon is able to cover i. Constraint (3.3) requires each state to have one WMD-CST, and Constraint (3.4) prevents a state from having more than one CERFP and/or HRF. Assuring that

one HRF is aligned with each FEMA region is accomplished via Constraint (3.5). The number of WMD-CST, CERFP, and HRF facilities to be sited is set by Constraint (3.6). Constraint (3.7) requires at least q^ℓ facilities from the current unit locations at echelon ℓ be maintained. Finally, Constraint (3.8) and (3.9) represent binary logical constraints for the decision variables.

Incorporating the minimum stand-off distance is accomplished in a manner similar to the method described by Lunday [49] in Chapter 3. We set the parameter $a_{jj} = 0$ as Lunday described but also set any $a_{ij} = 0$ if the corresponding d_{ij} is less than or equal to the minimum stand off distance. Defining this constraint through the parameter simplifies solving the model in Chapter 4.

3.6 Set Covering Model

The Set Covering Model provides a different look at the problem and finds the minimum number of additional teams needed to achieve full coverage. To account for the coverage provided by the existing structure we reduce the demands to nodes that are uncovered by the existing structure. Our SCP model then finds the minimum number of units needed to cover these uncovered demands. Coverage requirements are determined in the same manner as the MCLP model. The SCP utilizes the same sets, decision variables, and parameters from the MCLP model along with one additional set listed below.

3.6.1 Sets.

- U: Set of demand nodes uncovered by a current solution $\bar{y}$.

3.6.2 Model Formulation.

$$\min \sum_{\ell \in L} \sum_{j \in N} y_j^{\ell} \tag{3.10}$$

$$\text{subject to } \sum_{j \in N} a_{ij}^{\ell} y_j^{\ell} \geq 1, \qquad \forall \, l \in L, \, \forall \, i \in U, \tag{3.11}$$

$$y_j^l, \in \{0, 1\}, \qquad \forall \, j \in N, \tag{3.12}$$

The objective function (3.10) seeks to minimize the number of facilities needed in order to cover each demand, given a specified coverage radius. Constraint (3.11) requires each demand node to be covered by at least one facility, at each echelon. Finally, Constraint (3.12) defines binary logical constraints for the decision variables.

3.7 Parameter Development

- h_i : Population of each county was determined from the 2010 Census.

- d_{ij} : Distance between counties comes from the Center for Transportation Analysis Oak Ridge National Highway Network (NHN).

"The Oak Ridge National Highway Network is a geographically based analytic network of the major highways in the United States. It was developed at Oak Ridge National Laboratory to support analyses of a wide variety of highway transportation issues that require use of a network. It presently contains approximately 500,000 centerline miles of roadway and will, with varying degrees of accuracy, show the location of these roads and attribute detail about their characteristics. Although it includes many roads of lower class, it may be thought of fundamentally as an arterial network. The ultimate intent is to represent all rural arterials and most urban principal arterials, but not collectors or urban minor arterials unless they are part of through highways." [9]

Using this network we apply Floyd's algorithm to determine the shortest path between each node.

- r^{ℓ}_{max} : The maximum coverage radius comes from existing doctrine and accepted standards within the DoD. Distance is converted to time using a 50 mile per hour response speed. WMD-CST were evaluated against a five hour response window which translates to a maximum distance of 250 miles. CERFPs have a six hour response requirement which translates to a 300 mile maximum coverage distance. Finally, HRFs have a 12 hour response requirement which translates to a 600 mile maximum coverage radius.

  r^{w}_{max} : 250

  r^{c}_{max} : 300

  r^{h}_{max} : 600

- r^{ℓ}_{min} : The minimum stand-off distance is developed based on projected impacts from a 10 kiloton nuclear device. This is the most deadly of the 15 scenarios defined in the National Preparedness Guidelines [12] and is also the event for which the CRE can have the greatest impact. Planning guidance from the Federal Inter agency Committee Led by the Executive Office of the President [10] highlights a 10 kiloton device as the most likely nuclear device that would be used in a domestic terror attack. The significant damage from this device is estimated to occur within a three-mile radius, and the deadly fallout radius is estimated to extend for 10-20 miles. Given this information, we define a conservative minimum standoff distance to be 25 miles.

  r^{w}_{min} : 25

  r^{c}_{min} : 25

  r^{h}_{min} : 25

IV. Implementation and Analysis

4.1 Introduction

In this chapter we present an evaluation of the current CRE structure and identification of efficient modifications that can improve the coverage capability. We apply two scenarios to conduct this evaluation. The first scenario analyzes the structure in terms of the current coverage definition that is drawn from doctrine and DoD guidance. The second scenario accounts for the risk that exists if a CBRN incident neutralizes the capability of any CRE units within a specified distance of a targeted location. Additionally, we present an analysis of both the WMD-CST structure only, and the CRE in its entirety. The WMD-CST structure is worthy of a separate analysis because rapid response by CERFPs and HRFs depends on information from a WMD-CST, the first echelon to respond within the CRE. Additionally, the WMD-CST model requires fewer modeling assumptions which leads to a more accurate estimation of coverage.

4.2 Scenario Development

There is no current DoD guidance or doctrine that addresses planning for, or considering, the destruction of a CRE unit's capability due to a CRBN incident. Through the analysis of this second scenario we intend to represent the risk to CRE assets by a CBRN attack and thus the necessity to account for this risk into the future CRE structure decisions. Each scenario is explicitly defined as follows.

- Baseline Scenario: A CBRN incident does not impact any of the CRE units. Coverage is defined based on current doctrinal standards. The coverage radius for each team is below:

- WMD-CST coverage radius : 0 to 250 miles

- CERFP coverage radius : 0 to 300 miles

- HRF coverage radius : 0 to 600 miles

- Pessimistic Scenario: A CBRN incident will destroy the capability of any CRE unit located within a specified distance, and CRE coverage is reliant upon the closest unit outside this minimum stand-off distance. The updated coverage radius for each echelon is below.

  - WMD-CST coverage radius : 25 to 250 miles

  - CERFP coverage radius : 25 to 300 miles

  - HRF coverage radius : 25 to 600 miles

These two scenarios will highlight the level of coverage of the current structure and risk that may exist.

4.3   Data Sources and Assumptions

We obtained the data used in this analysis from unclassified open-source resources; it provides an approximation of the true system but is not an exact representation. The road infrastructure network [9] utilized consists of 3109 nodes that represent the population cores for counties in the Continental United States and the District of Columbia. The arc length between nodes is determined using US highway road distance. Population estimates for each county are taken from the 2010 US Census and are geographically represented in Figure 4. Counties were classified by the CDC's 2013 NCHS UrbanRural Classification Scheme for Counties [16]. CRE unit locations [7] are estimated to exist at the population center of each county in which they are based and do not depict their precise locations. We further assume the road network

data is current, and that CRE elements will traverse the network unimpeded at an average rate of speed of 50 mph.

Total Population = 306,675,006

■ County Pop ≥ 1M
■ County Pop ≥ 250k
■ County Pop ≥ 50k
■ County Pop ≥ 10k
□ County Pop < 10k
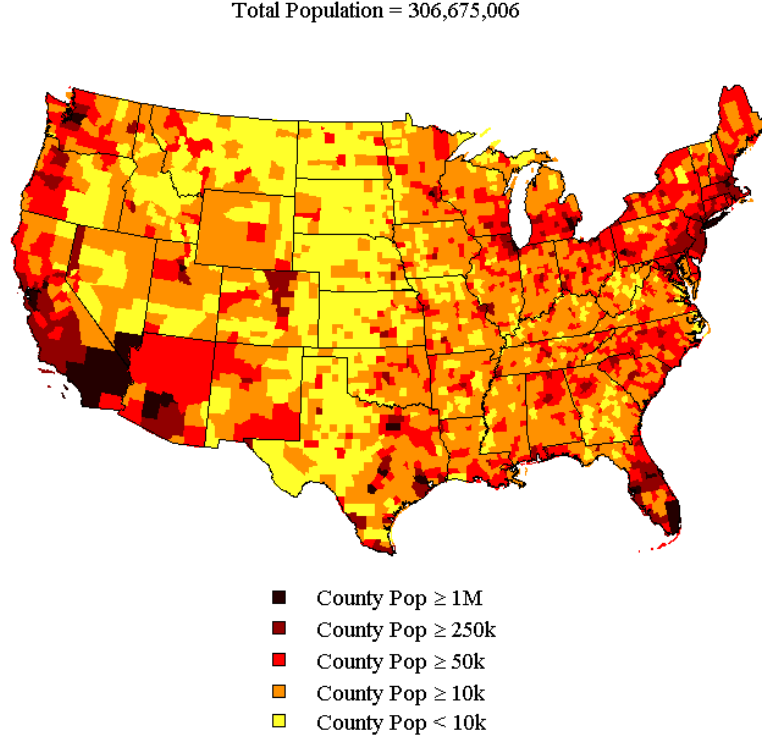
Figure 4. US Population by Counties [8]

4.4   Optimal Solutions

Solutions were found on a PC with an Intel Xeon Processor E5-1620 and 32 GB of memory using the commercial solver CPLEX (Version 12.6) [44] called through Matlab. All solutions reported are within at least a relative optimality tolerance of 0.49%. This tolerance was instituted to prevent excessive run times that occurred when running the model using the Pessimistic Scenario, which included the CCP

constraint. The CCP is a NP-Hard problem and certain instances were not solvable to optimality given the computing resources available.

4.5   Evaluation of Solutions

In our analysis we consider two additional measures outside the two objectives, maximizing population covered and minimizing cost of modifications, of our model formulation. These measures are not objectives of our formulation but will be used to demonstrate the value of incorporating the Pessimistic Scenario into future planning. First, we use the population colocated with each CRE unit as a measure of the risk. Since we are assuming the probability of a CBRN event in a county is correlated to the population of that county, the population size colocated with a CRE unit represents the risk of an attack at a CRE unit's location. Thus, the risk of a CRE unit's capabilities being neutralized by a CRBN event are correlated with the size of the colocated population. Finally, to assess redundancy of coverage, we evaluate the percentage of the population that is covered by more than one team,"double covered".

4.6   WMD-CST Coverage

4.6.0.1   Support Across State Boundaries.

The following section reviews the assumption about coverage across state boundaries using the Baseline Scenario. We conduct this examination to demonstrate the significant reduction in coverage that results from a myopic view of providing coverage from only internal state assets, and thus the necessity of a holistic, enterprise approach.

Assuming WMD-CSTs can only provide coverage inside their respective state, results in approximately 285 million people or 93% of the population being covered, as depicted in Figure 5. In Figure 5 covered counties are highlighted in green.
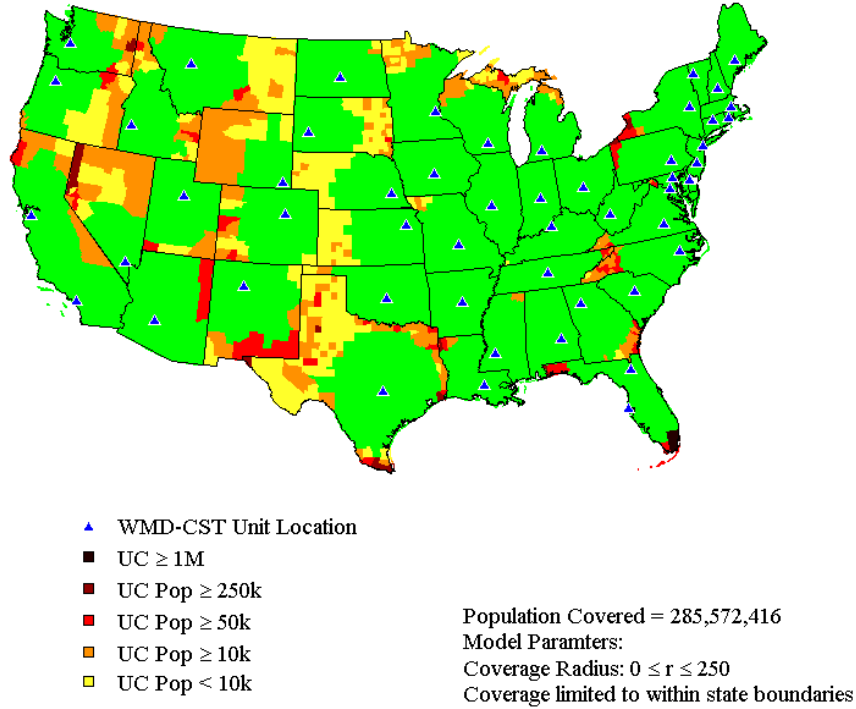
Figure 5. Coverage provided by WMD-CSTs with coverage limited to within state boundaries

Removing this restriction and allowing teams to cover locations outside the states in which they are based improves coverage by over 8 million people to approximately 294 million or 95.88% of the population. Additionally, the total number of uncovered counties reduces from 473 in the absence of coordination between states for WMD-CST response with no support occurring across State Boundaries to 230 with it. This increase in coverage demonstrates the necessity for states to share resources in order to better protect the American population. For the remainder of this study we assume CRE assets can support counties across state boundaries. We similarly assume that HRFs can support counties across FEMA boundaries.

4.6.1   WMD-CST Baseline Scenario.

4.6.1.1   Baseline Coverage: Current Unit Locations.

As mentioned in the previous section, the current structure covers 294 million or 95% of the population, as depicted in Figure 6.
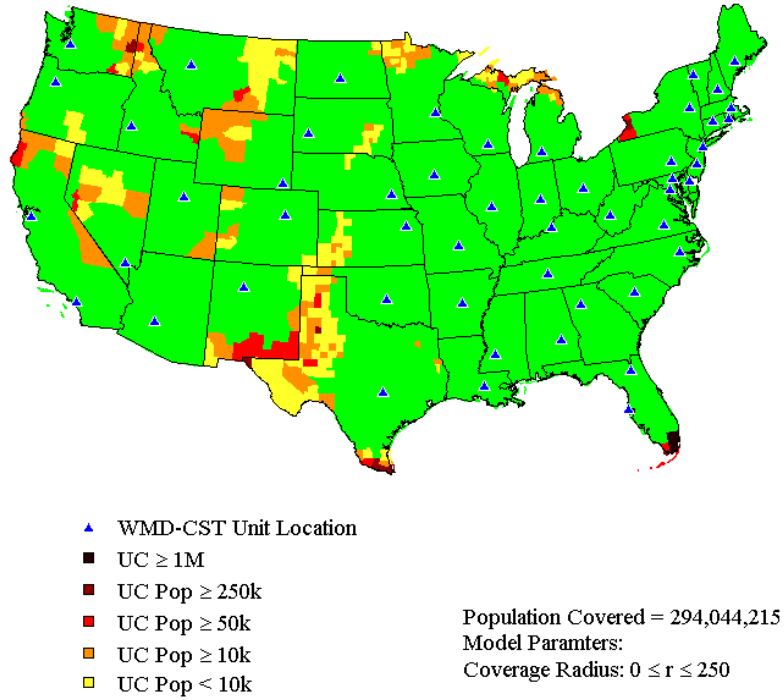
Figure 6. WMD-CST Current Coverage Baseline Scenario

Additionally, only 28 of the 230 uncovered counties have populations above 50,000, and of those 28, only 8 have populations above 250,000. The two largest uncovered counties are located in southern Florida, where more than four million people are not covered in Boward and Miami-Dade County. This is especially interesting given that Florida already has two WMD-CSTs. Outside of southern Florida the current

structure using the existing definition of coverage covers the most likely targets of a CBRN attack quite well.

4.6.1.2 Baseline Coverage: Optimal Unit Locations.

Since the current structure does not provide full coverage, an analysis of an optimal structure using the current number of WMD-CSTs will provide insight into the quality of the current structure. The optimal structure is defined to maximize coverage of the population using the existing number of WMD-CSTs with at least one team located in each state. Using our model we are able to increase coverage to over 306 million people or 99.99% of the population, as depicted in Figure 7. This optimal structure, which requires 25 WMD-CST relocations, leaves only five counties, each with a population under 10,000, uncovered.

It is interesting to note that every county in Florida and New York, states that both currently have two WMD-CSTs, could be covered with only one team based within their respective state boundaries using this optimal structure. While all modifications in this solution may not be feasible due to other considerations (e.g., the availability of federal facilities at a proposed WMD-CST location), it demonstrates that improvements exist for the current structure.
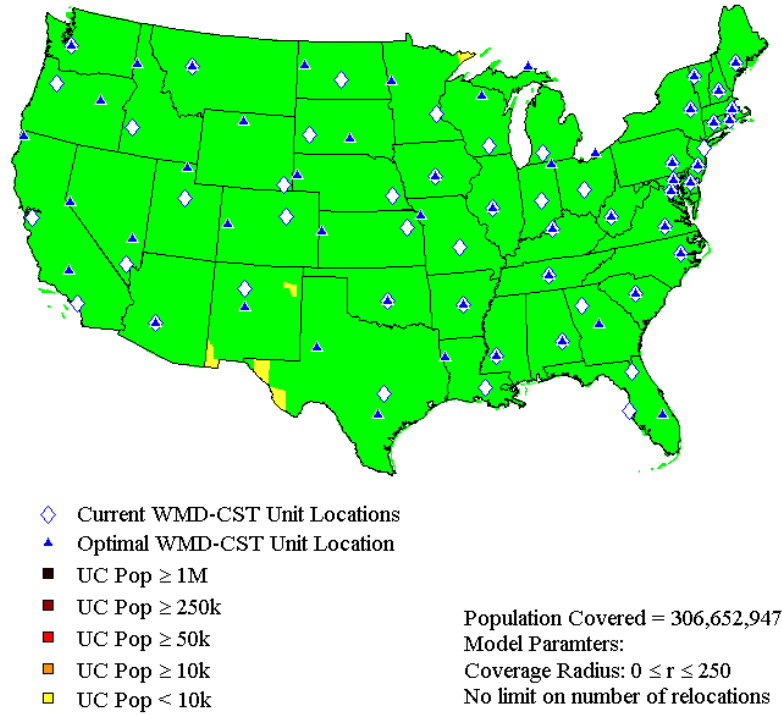
Figure 7. WMD-CST Optimal Locations Baseline Scenario

4.6.2 WMD-CST Pessimistic Scenario.

We now analyze the Pessimistic Scenario wherein a WMD-CST must be located outside the minimum stand-off distance to provide coverage for a county. This added constraint highlights areas, at which WMD-CSTs are located in close proximity, that are at risk of being uncovered if any CRE unit within the minimum stand-off distance was rendered ineffective by a CBRN attack. The minimum stand-off distance was developed based on projected impacts from a nuclear device detonation and estimated to be 25 miles. The maximum coverage radius remains at 250 miles as in the previous Scenario.

4.6.2.1   Pessimistic Coverage: Current Unit Locations.

With this additional constraint, coverage by the current WMD-CST structure drops to 278 million people or approximately 90.93% of the US population, as depicted in Figure 8. This means approximately 5% of the population is at risk of being uncovered if WMD-CSTs located within the 25 mile minimum stand-off distance are rendered non-functional by a CBRN incident.
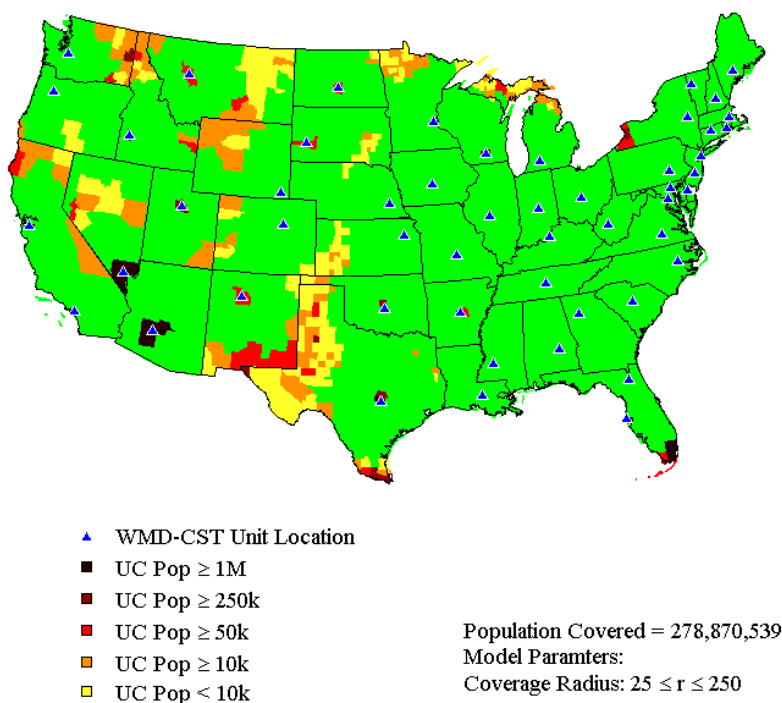
Figure 8. WMD-CST Current Coverage Pessimistic Scenario

This is particularly significant because the change in coverage exists primarily in densely populated areas. Five additional counties with a population greater than 1 million and seven counties with a population greater than 250,000 people are, in

this scenario, uncovered. These uncovered counties include major cities such as Los Angeles, Las Vegas, Phoenix, Oklahoma City, and Austin, each of which is a realistic target for a terrorist attack.

4.6.2.2 Pessimistic Coverage: Optimal Unit Locations.

It is clear that this additional coverage constraint reduces coverage capability significantly. As with the baseline analysis, we compare the current unit locations to an optimal structure to determine how much the structure could improve. This optimal structure again uses the current WMD-CSTs and requires at least one team to be located in each state. The optimal structure covers over 306 million people or 99.89% of the population with 50 relocations, as depicted in Figure 9.

While the current coverage in terms of the Pessimistic Scenario highlights significant shortfalls in coverage, the optimal structure demonstrates it is possible to cover a significant portion of the country with the current number of assets. Additionally, the optimal structure covers all counties with populations greater than 50,000.

Note that the optimal solution for the Baseline Scenario yields only a 0.1% improvement in the population covered when compared to the optimal solution for the Pessimistic Scenario. The advantage of applying the Pessimistic Scenario to site WMD-CSTs is it reduces the risk to WMD-CSTs by moving them to less populated locations. Without the standoff restriction, the optimal set of WMD-CSTs were colocated with a population of approximately 15 million and with the standoff restriction, the colocated population reduces to approximately 10 million. If we assume the risk of an attack is correlated with the population of the city, then the minimum standoff model significantly reduces the risk to the total WMD-CST enterprise. Additionally, the percentage of the population that is "double covered" increases from 60% to 65% using the Pessimistic Scenario. The comparison of optimal solutions from the two

scenarios demonstrates the value of incorporating the Pessimistic Scenario into future planning because it reduces the risk of attack to WMD-CSTs while covering a significant portion of the population.
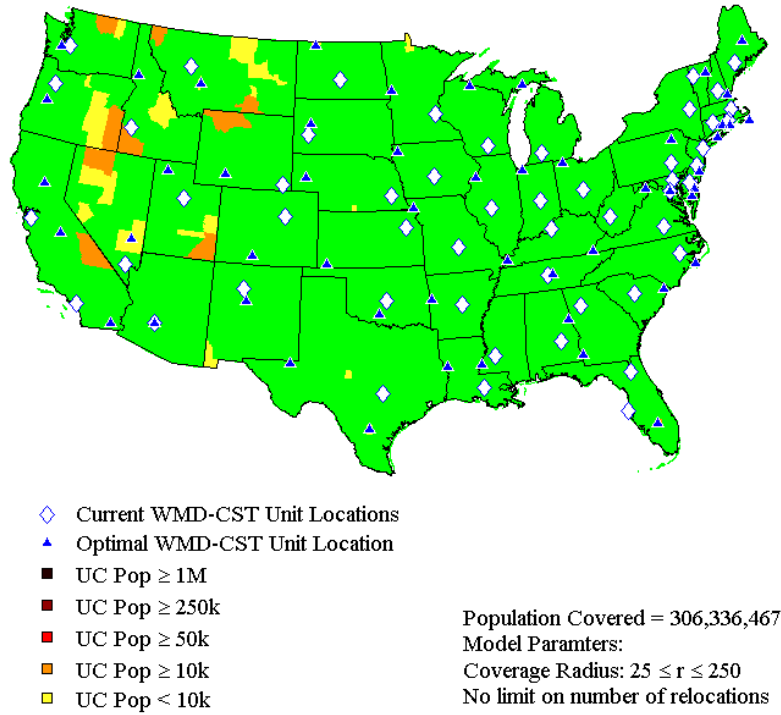

Figure 9. WMD-CST Optimal Locations Pessimistic Scenario

4.6.3 WMD-CST Relocation Trade-Off.

Given that the WMD-CST structure already exists, any modification to the structure will incur costs. Thus, moving a significant portion of the force is likely not a viable option. To identify the trade-off between coverage gained and relocation costs, we vary the number of teams that must remain in their current location from 0 to 51 (the Washington DC team only has one possible location) and resolve the model for

each instance and each scenario. Figure 9 represents the percent of the population that can be covered by WMD-CSTs for both the Baseline and Pessimistic Scenarios as the allowed number of relocations from the existing structure increases.
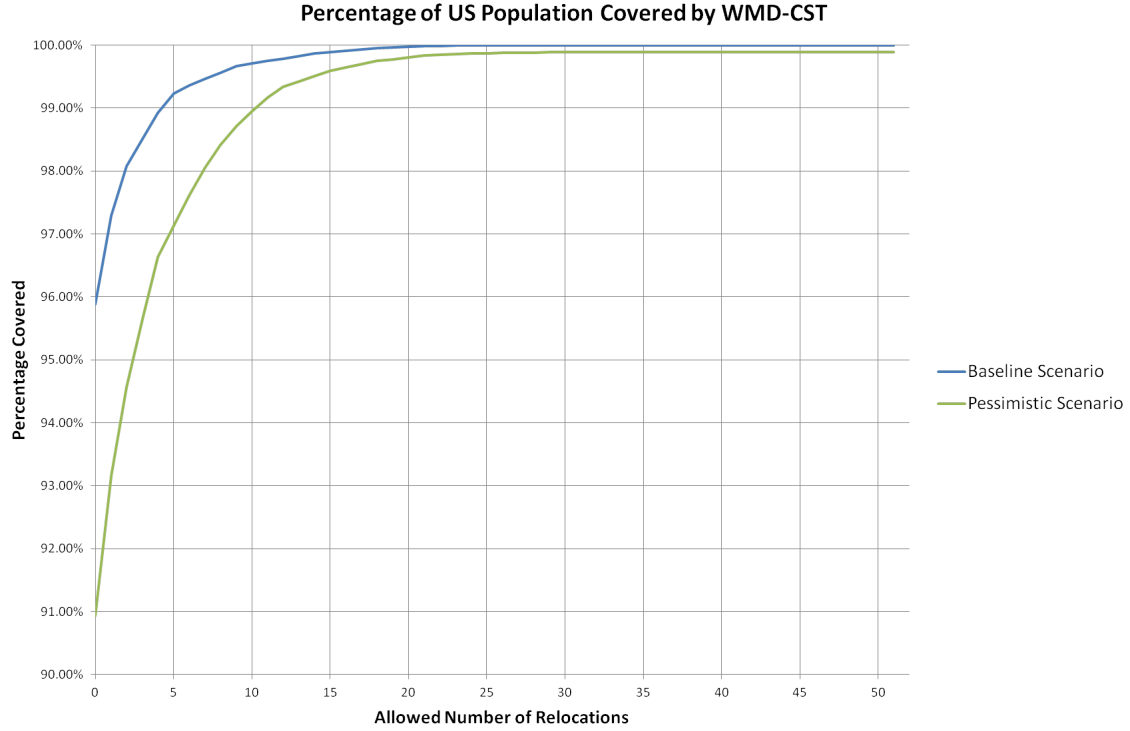
Figure 10.   Percentage of the population covered as allowed number of relocations increases

For more than 32 allowed relocations, the coverage for each model sees no improvement. Furthermore, after 11 allowed relocations coverage in both scenarios exceeds 99%. This significant gain in coverage can by achieved with less than a 20% modification to the current structure. In Figure 11 we further highlight the marginal increase for each additional relocation.
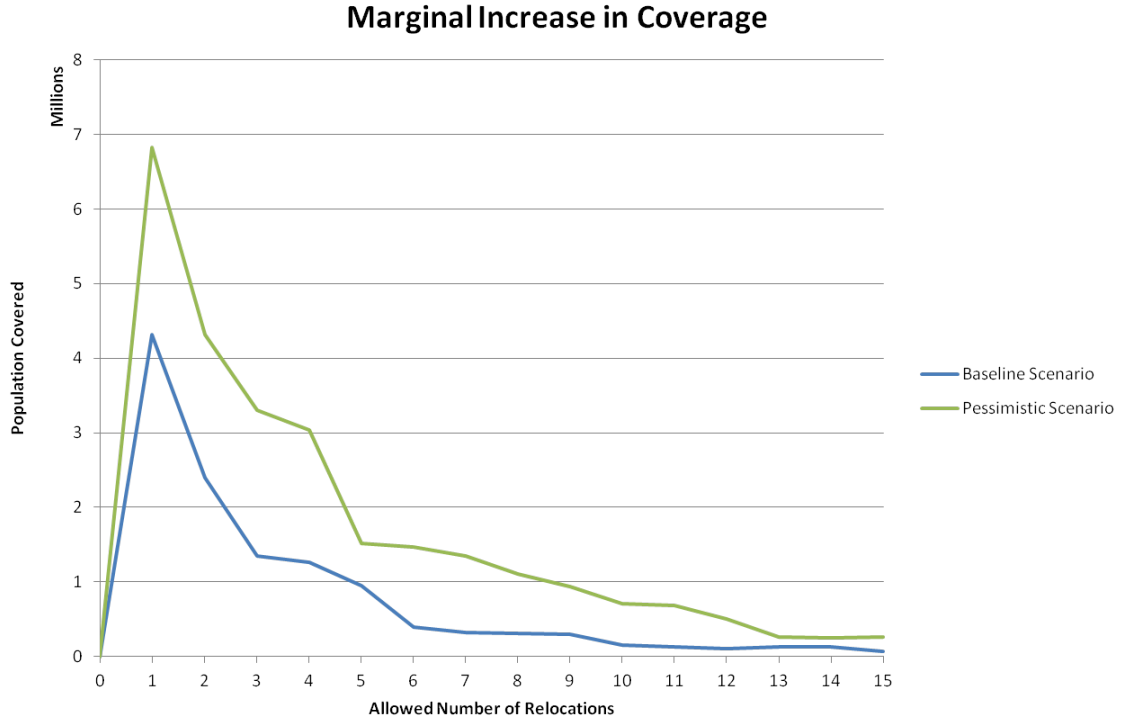
Figure 11. Increase in number of people covered per additional allowed WMD-CST relocation

4.6.4 Sensitivity on Coverage Parameters.

Within the Pessimistic Scenario, both the minimum stand-off distance and the maximum coverage radius impact the coverage provided by the CRE. Since both are estimates, an investigation into the impact these parameters have on the solution is warranted. We apply Response Surface Methodology (RSM) to examine this impact. Since we are only concerned with minimum stand-off distance and maximum coverage radius, we choose to hold all other model inputs constant. To accomplish this, we hold all WMD-CSTs at their current locations and consider the Pessimistic Scenario. Current WMD-CSTs locations are used because changes to the system are largely based off of this initial assessment. For example, if coverage is above a certain threshold we have no interest in changes to the structure and further analysis is

70

unwarranted.

Selection of a design for a response surface involves many considerations. First, we must determine the budget for experiments. The model is deterministic, and thus there is no need for replication. Additionally, given that the objective function value is now a function of minimum stand-off distance and the maximum coverage radius only, the computation of coverage is trivial. This facilitates the use of a large number of runs with little computational time, and thus we are not constrained by a run limit.

Next we determine the region for experimentation. We decide to center our design region on the settings used in the previous analysis: a minimum stand-off distance at 25 miles and a maximum coverage radius at 250 miles. We are interested in examining a large area of the response surface and choose to set the limits for the minimum stand-off distance $\pm$ 25 miles from the design center and ± 50 miles from the design center for the maximum coverage radius. The design region is highlighted in Table 1:

Table 1. Coded Design Variables

Coded Value	Minimum Stand-off Distance	Maximum Coverage Radius
-1	0	200
0	25	250
1	50	300

Since the goal is to characterize the response surface over a fairly wide range, and it is likely that a first or second order polynomial will not sufficiently characterize the region, we consider a space-filling design. These designs are often used in deterministic computer models when the shape of the response surface is unknown and thought to be complex [53]. We choose a Latin Hypercube design with 200 runs because of its space filling properties, as depicted in Figure 12.
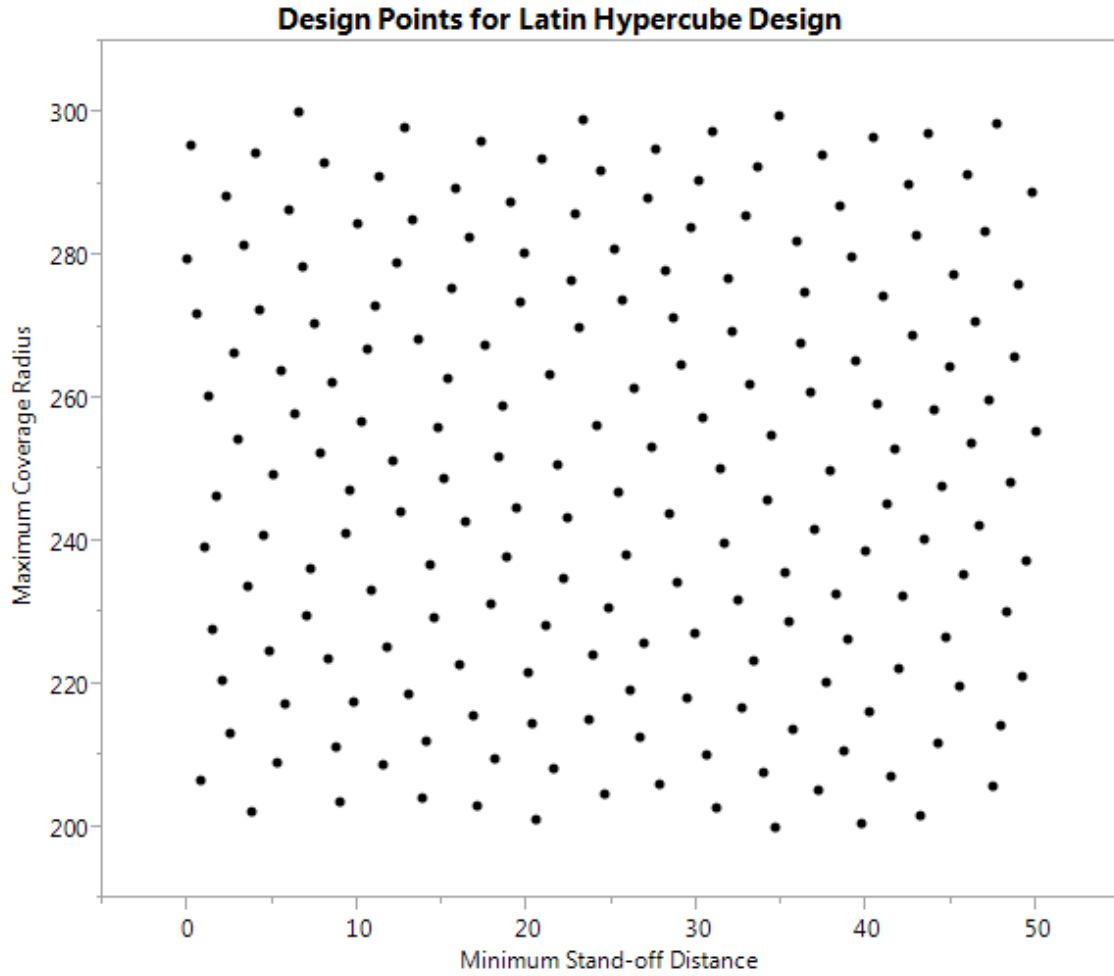
Figure 12. Latin Hypercube Deign

After running the experiments we fit a surface to our response using a Gaussian Process model. These are useful in deterministic computer models because they fit the surface through each point. The estimated surface is not an exact representation of the true surface but allows for an examination of the region. This Gaussian Process surface is depicted in Figure 13. The estimated response surface highlights a dramatic decrease in coverage at a minimum stand-off distance of greater than 39 miles. Outside of this region the minimum stand-off distance parameter is not extremely sensitive to adjustments. Examining the effect of maximum coverage radius we notice that, above 275 miles the objective function value becomes fairly insensitive to the minimum

72

stand-off distance.
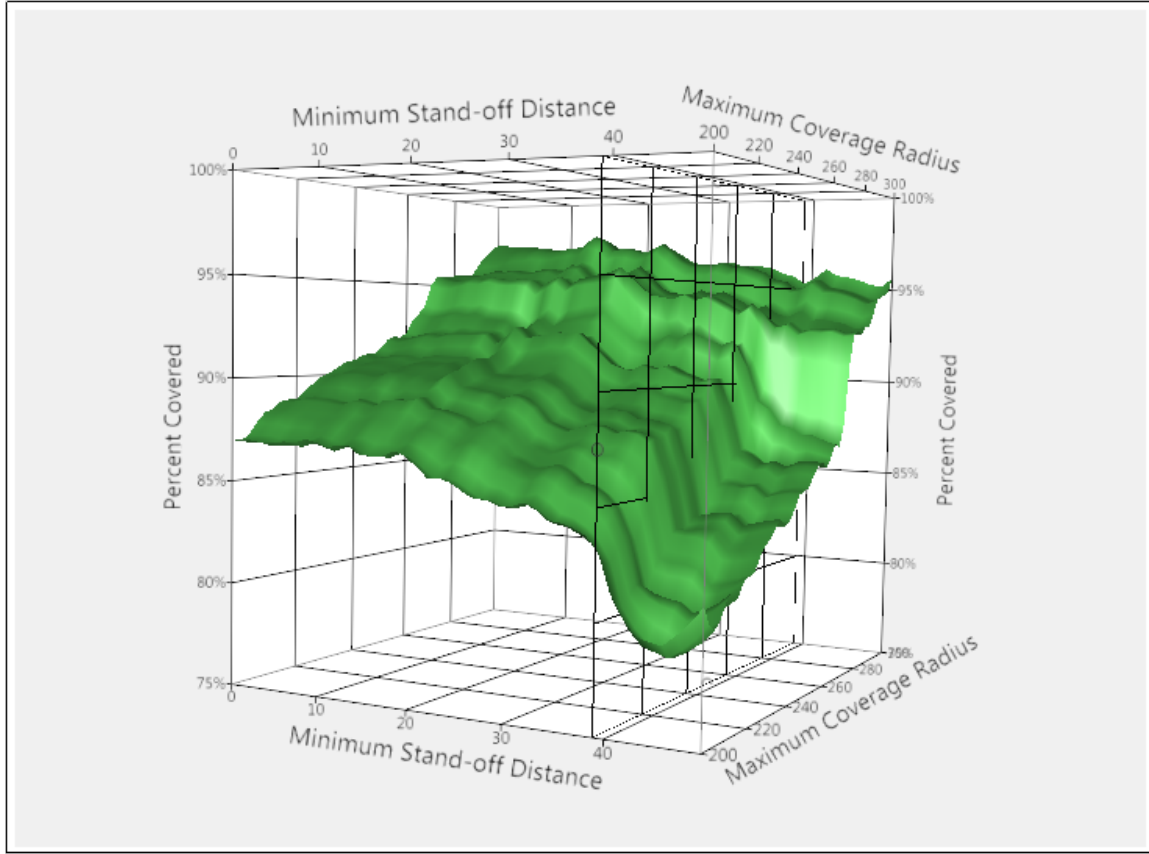
Figure 13. Gaussian Process Surface for the current unit location objective function value under the Pessimistic Scenario

Next we fit an 8th order polynomial and explore the region as we hold one of these parameters constant, as depicted in Figure 14. The graph on the left side of Figure 14 depicts coverage as maximum coverage radius is held at 250 miles and minimum stand off distance is varied from 0 to 50 miles. The graph on the right side of Figure 14 depicts coverage as minimum stand-off distance is held constant at 25 miles and maximum coverage radius is varied from 200 to 300 mile. We observe again the sensitivity of the response to a minimum stand-off distance greater than 39 miles. We also note that coverage appears to have a pseudo linear relationship with maximum coverage radius. The change in coverage appears to be dramatic

but we must remember we are experimenting over a large range of the experimental region. For example the maximum coverage radius range, in terms of hours, varies from a four hour to six hour response. A two hour difference in response can have a dramatic effect on lives saved in a catastrophic CBRN event. Minor deviations in either parameter result in small changes in coverage, which leads us to conclude the model is fairly insensitive to minor deviations in these two parameters.
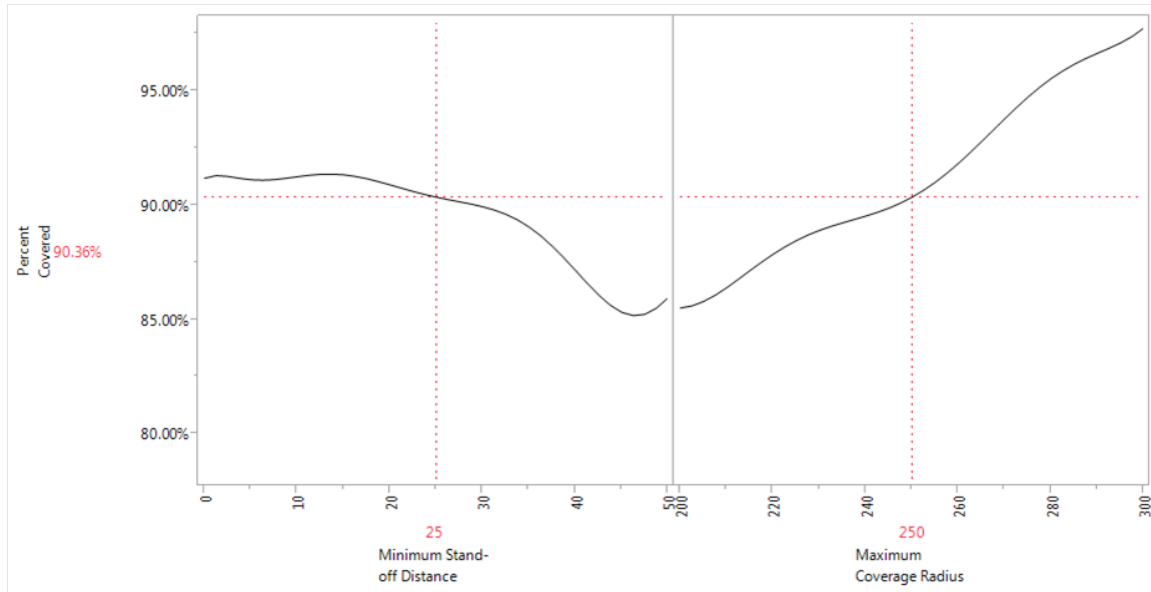

Figure 14. Response Surface using an 8th order Polynomial Fit with respect to minimum stand-off distance and maximum coverage radius, respectively, for WMD-CSTs

4.7 CRE Coverage

Similar to the WMD-CST echelon coverage, we analyze the coverage provided by the CRE in its entirety using the Baseline and Pessimistic scenarios. Each echelon has a respective coverage radius that is based on doctrine and current DoD guidance. The minimum stand-off distance for the Pessimistic Scenario remains unchanged from the WMD-CST analysis and is the same for each echelon. Different from the WMD-CST model, a county must be covered by a WMD-CST, CERFP, and HRF in order for it

74

to be considered covered. Thus, the coverage estimate for this model will always be less than or equal to the model that only considers WMD-CST coverage. We remind the reader that each HRF has a CERFP capability within its structure. Thus, a HRF located within the CERFP coverage radius can provide both CERFP and HRF echelon coverage. If the closest HRF exists outside the CERFP coverage radius, but within the HRF coverage radius it will provide HRF-echelon coverage only.

4.7.1 CRE Baseline Scenario: Current CRE Unit Locations.

The current coverage provided by the CRE is just over 269 million or 88% of the population, as depicted in Figure 15. A total of 22 of the 706 uncovered counties have populations exceeding 250,000.

Different from the previous analysis, when examining the entire CRE, there is additional risk in densely populated areas such as San Diego and Phoenix. Furthermore, Montana, North Dakota, South Dakota, Oklahoma, and New Mexico are all states wherein the majority of the population is uncovered when the entirety of the CRE is considered. These states are not the most likely for a population-oriented terrorist attack, but the lucrative nature of other CBRN events in these states may merit concern and adjustment to the CRE to improve coverage. Finally, similar to the WMD-CST analysis, we note the risk that exists in the densely populated area of southern Florida.
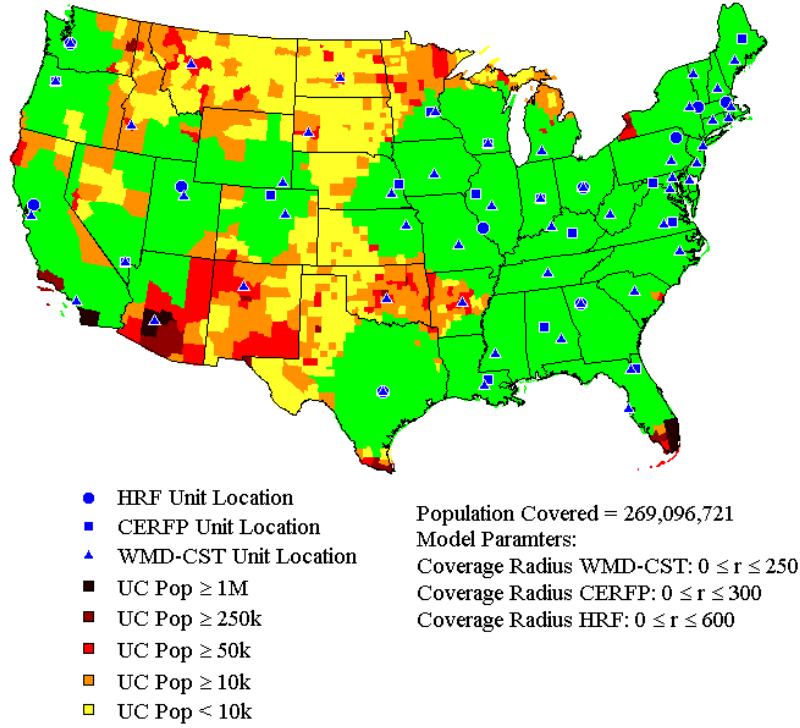
Figure 15. CRE Current Coverage Baseline Scenario

4.7.2 CRE Baseline Scenario: Optimal CRE Unit Locations.

We further evaluate the current structure by comparing it to an optimal structure that utilizes the same number of units at each echelon. The optimal structure covers 99.93% of the population as depicted in Figure 16. This structure requires 47 WMD-CST relocations, 15 CERFP relocations, and 10 HRF relocations. This equates to relocating the entire structure less 5 WMD-CSTs.
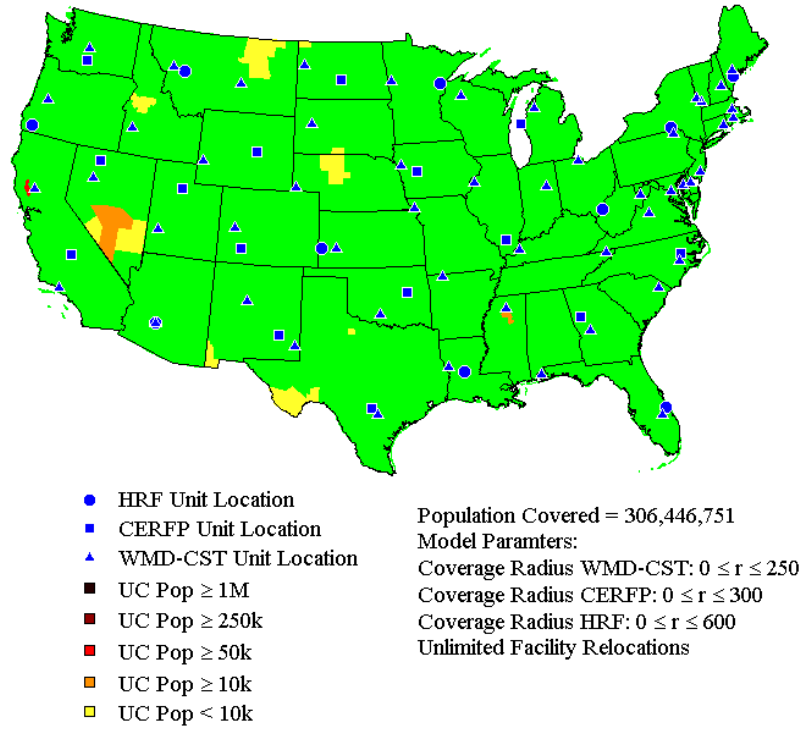
Figure 16. CRE Optimal Coverage Baseline Scenario

This structure covers all counties with populations greater than 250,000 and leaves only one county with a population greater than 50,000 uncovered. This demonstrates that significant improvements exist within the current structure.

4.7.3   CRE Pessimistic Scenario: Current CRE Unit Locations.

We now apply the Pessimistic Scenario to the current CRE unit locations which results in 83% of the population being covered as depicted in Figure 17. This represents approximately 5% decrease from the Baseline Scenario when accounting for risk to CRE assets and their coverage capabilities. A total of 35 counties with population greater than 250,000 are uncovered; this is an increase of 13 counties from the

77

Baseline Scenario.

HRF Unit Location
CERFP Unit Location
WMD-CST Unit Location
UC Pop ≥ 1M
UC Pop ≥ 250k
UC Pop ≥ 50k
UC Pop ≥ 10k
UC Pop < 10k

Population Covered = 255,646,124
Model Paramters:
Coverage Radius WMD-CST: $25 \leq r \leq 250$
Coverage Radius CERFP: $25 \leq r \leq 300$
Coverage Radius HRF: $25 \leq r \leq 600$
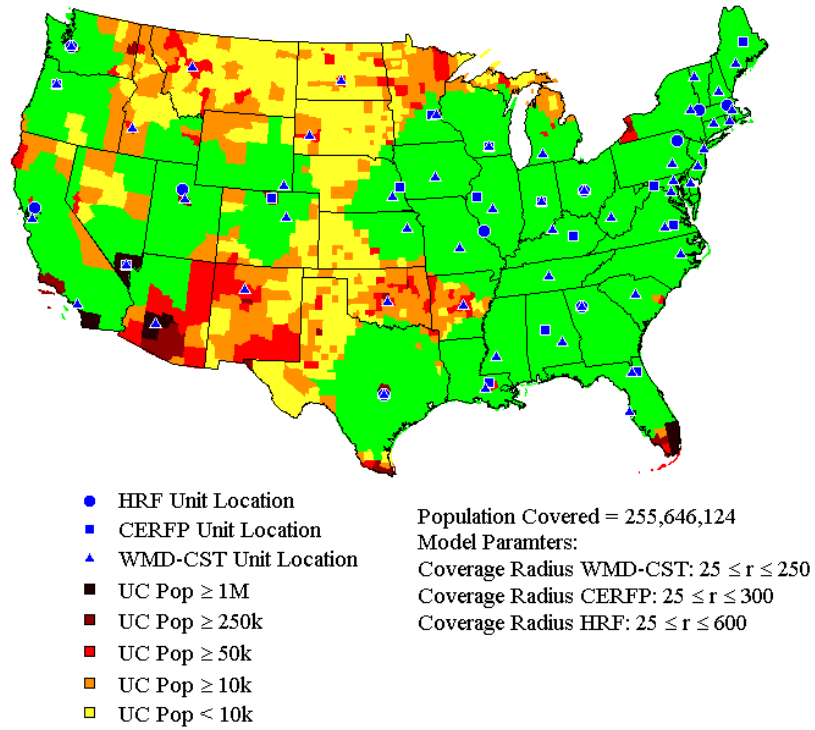
Figure 17. CRE Current Coverage Pessimistic Scenario

4.7.4 CRE Pessimistic: Optimal CRE Unit Locations.

We again identify an optimal structure to compare to the current structure. The optimal CRE unit locations covers 99.46% of the population, as depicted in Figure 18. This structure relocates all but four WMD-CSTs.
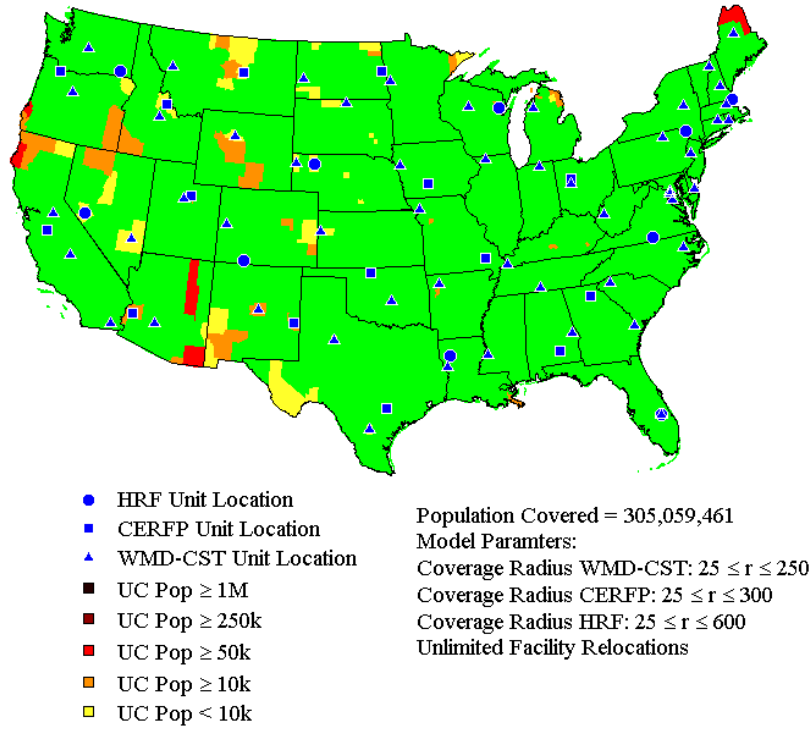
Figure 18. CRE Optimal Coverage Pessimistic Scenario

The coverage provided by the Pessimistic Scenario is only 0.27% less than the Baseline scenario but the Pessimistic Scenario again places CRE units in less vulnerable locations. This is measured by the total population CRE units are colocated with. The Baseline Scenario colocates CRE units with 18.7 million people compared to 12.4 million using the the Pessimistic Scenarion. Similar to the WMD-CST only model this is a significant reduction. It is also worth noting the current CRE unit locations are colocated with 44.8 million people, thus, the reduction in colocated population from current unit locations to the optimal Pessimistic Scenario unit locations is approximately 72%. Additionally, the percentage of the population that is double covered by all three CRE echelons is 10% for the Baseline Scenario and 20% for

the Pessimistic Scenario. This demonstrates the value in applying the Pessimistic Scenario to future planning.

4.7.5 Uncovered Counties by Echelon.

Since CRE coverage depends on three different echelons, note that the coverage maps in Figures 15 - 18 do not depict which echelon or echelons are not providing coverage to an uncovered county. In Figure 19, we represent the percent of the population uncovered by each each echelon across each of the four instances previously considered.
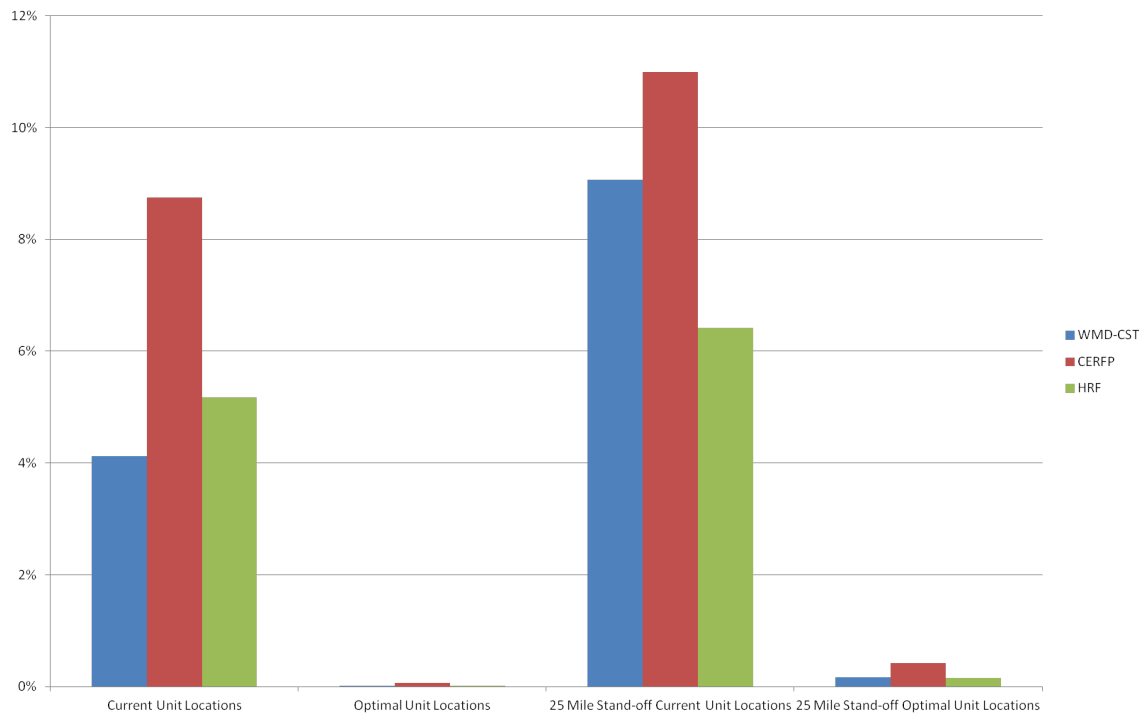

Figure 19. Uncovered population by unit type

For each scenario, the CERFP echelon is the most in need of modifications to improve coverage.

4.7.6 Resources Required for Full Coverage.

Since the optimal solutions did not achieve full coverage for the entire population, an examination of the number of teams needed to achieve full coverage is warranted. Moreover, political bureaucratic obstacles may preclude possible unit relocations and force all modifications to occur by establishing additional teams. We therefore identify the minimum additional teams needed to achieve full coverage in the Baseline and Pessimistic Scenario for both the current unit locations and optimal unit locations. Figure 20 depicts the additional teams needed to achieve full coverage for the four instances previously analyzed.
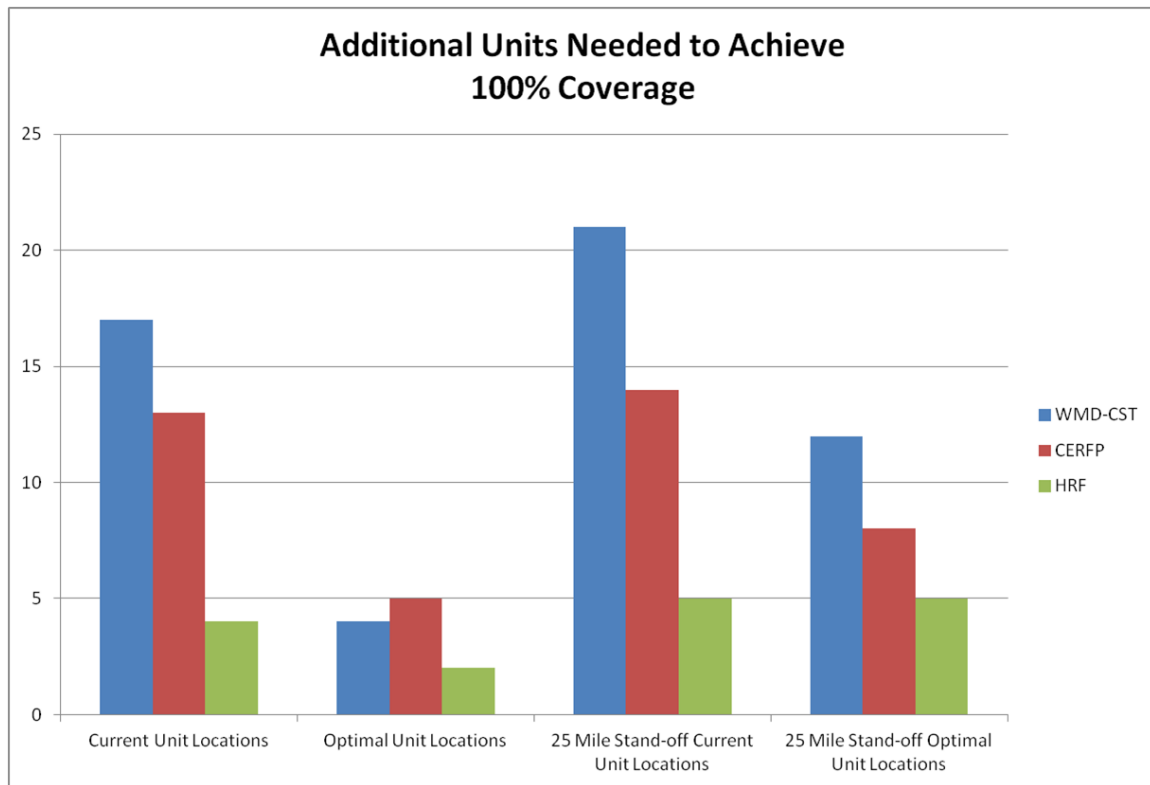
Figure 20. Additional units needed to achieve full coverage

To achieve full coverage with current unit locations in both scenarios, at least 30 additional teams of varying types are need. The optimal solutions require the

addition of fewer teams but require the relocation of at least 72 total CRE units in both instances.

None of these solutions are very cost effective and thus are not likely to be implemented. We now seek to balance an increase in coverage with the cost of modifications.

4.7.7 Myopic View of Each Echelon.

To further analyze the trade-off between relocations at each echelon and coverage, we construct a myopic view for each echelon. This myopic view is examined using the Pessimistic Scenario since it was shown to be the more useful scenario. As we consider each echelon we assume the other echelons provide full coverage, and thus coverage is only dependent on the echelon under consideration. This will highlight the minimum number of relocations at each echelon necessary to achieve a certain level of coverage. We use this method due to the computationally expensive process of exploring all 7,800 combinations of WMD-CST, CERFP, and HRF locations. By comparing myopic views we can establish the upper bound on coverage for a given number of relocations at each echelon. This allows a decision maker to visualize the range of alternatives and the corresponding best case coverage estimate for each alternative. In this analysis we seek to obtain 98% coverage as a goal for each echelon, but other minimum coverage standards could be considered.

4.7.7.1 Myopic View: HRF.

Figure 21 depicts coverage as the number of HRF relocations increases from 0 to 10. With five relocations we can improve coverage well above 99%, and with three relocations coverage improves to just over 98%. This indicates the maximum number of HRF relocations is likely not greater than five, and three is relatively efficient to improve HRF echelon coverage.

## HRF Coverage Myopic View: Pessimistic Scenario
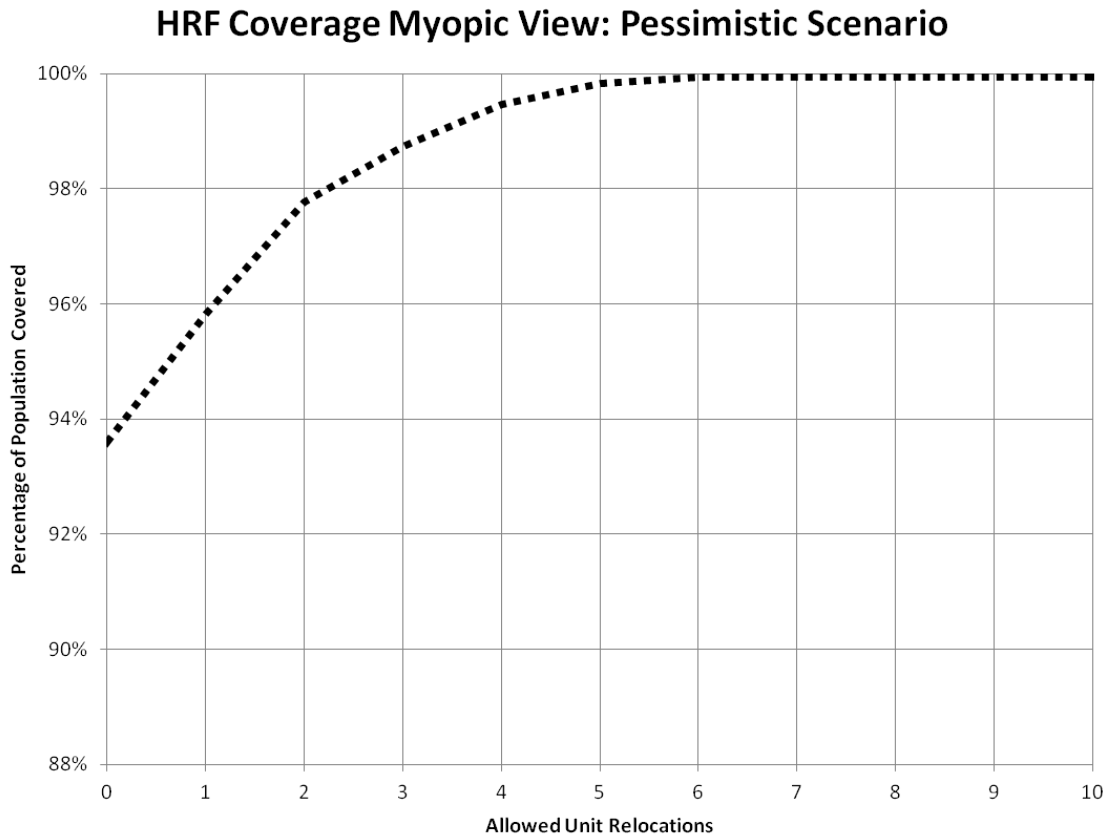
Figure 21. HRF Myopic View

4.7.7.2 Myopic View: CERFP.

It is important to again note that the CERFP echelon coverage is impacted by HRF unit locations. Thus, we vary the allowable CERFP relocations from 0 to 15, while we vary the allowable HRF relocations from 0 to 10. Figure 22 highlights how coverage is influenced by the CERFP echelon. Relocating up to four HRFs has a significant impact on the coverage provided by CERFPs but after that point coverage is primarily a function of CERFP relocations. Additionally, as the number of CERFP relocations increases, the impact of HRF relocations diminishes. From this, we determine approximately five CERFPs and three HRFs relocations are needed to achieve approximately 98% coverage.
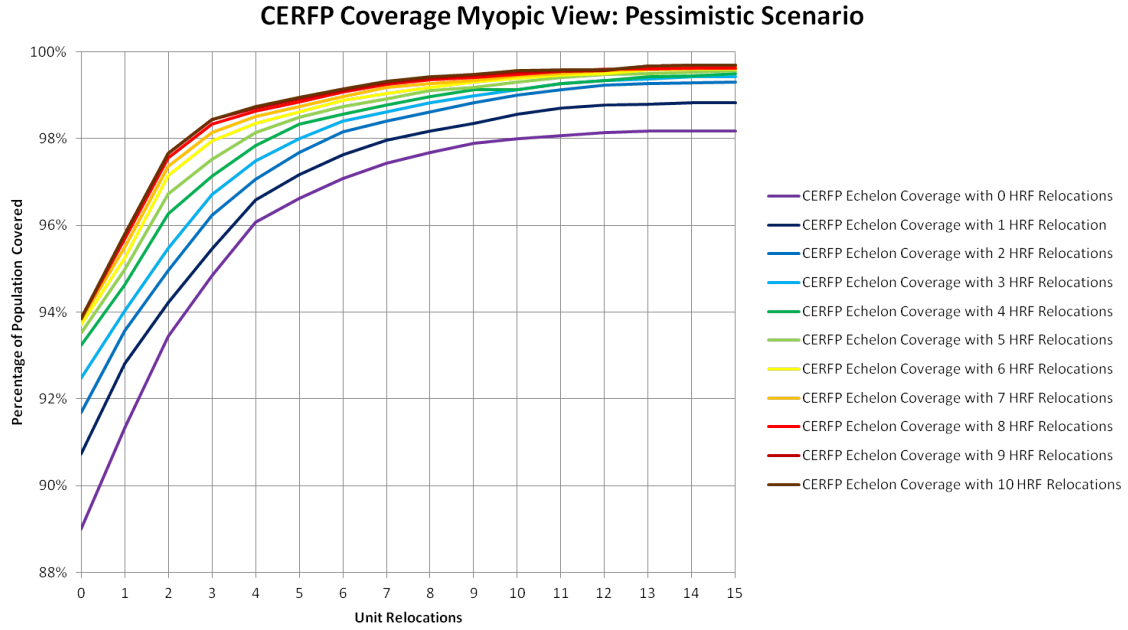
Figure 22. CERFP Myopic View

4.7.7.3   Myopic View: WMD-CST.

Finally, we analyze the WMD-CST only structure. The reader may recall this analysis is identical to the analysis conducted in the WMD-CST only model. We present Figure 23 as an updated representation of Figure 9 under the Pessimistic Scenario.

WMD-CST Coverage Myopic View: Pessimistic Scenario
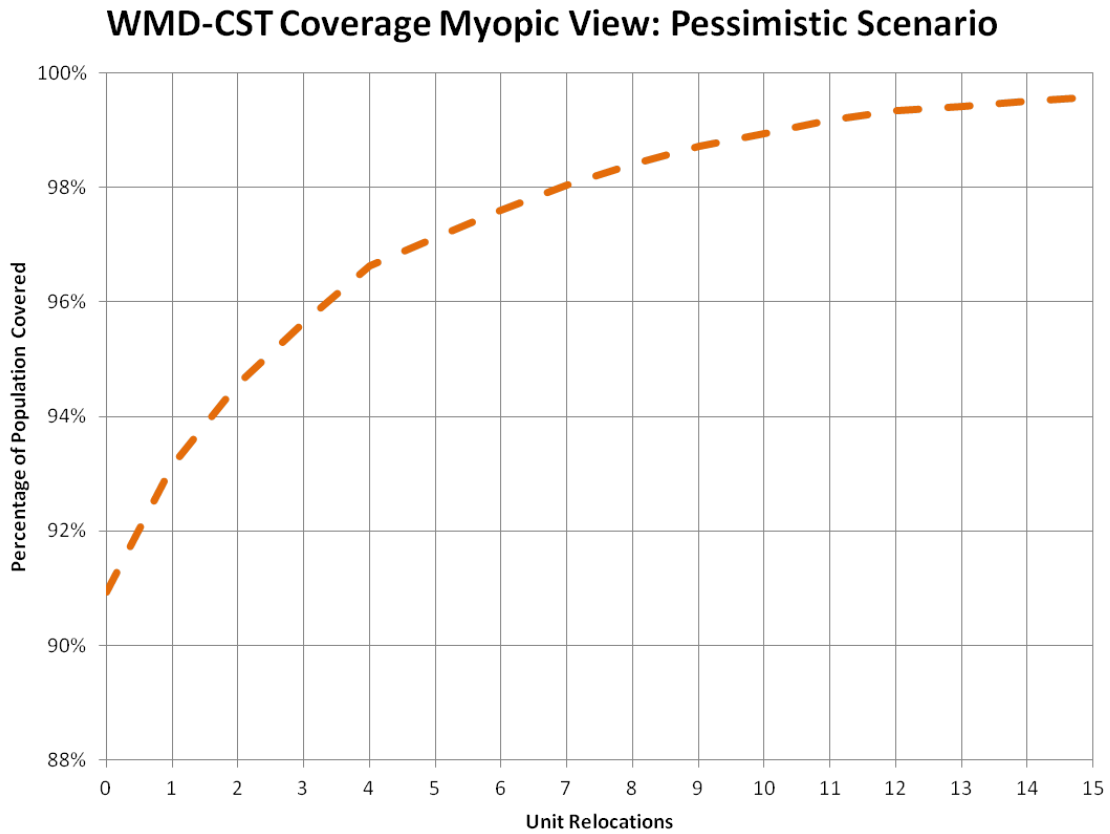
Figure 23. WMD-CST Myopic View

We can achieve 98% coverage with seven WMD-CST relocations.

4.7.7.4   Myopic View: Full CRE.

Combining each myopic view, we can now examine which echelon is driving coverage for a specific number of relocations, as depicted in Figure 24. It is important to note Figure 24 highlights the upper bound on coverage for a specified number of relocations at each echelon. Some counties are uncovered by multiple units and, thus, adding coverage at one echelon may not add coverage for the full structure. The combined myopic views identify the minimum number of relocations necessary at each echelon to achieve a specified coverage level.

As previously suspected, the CERFP echelon is the most in need of improvement. To achieve greater than 98% coverage we need to relocate at least three HRFs, five CERFPs, and seven WMD-CSTs.

Maintaining the same objective function and constraints while imposing our lower bound of at least three HRFs, five CERFPs, and seven WMD-CSTs relocations we achieve coverage of 95.44%.

Coverage Myopic View: Pessimistic Scenario
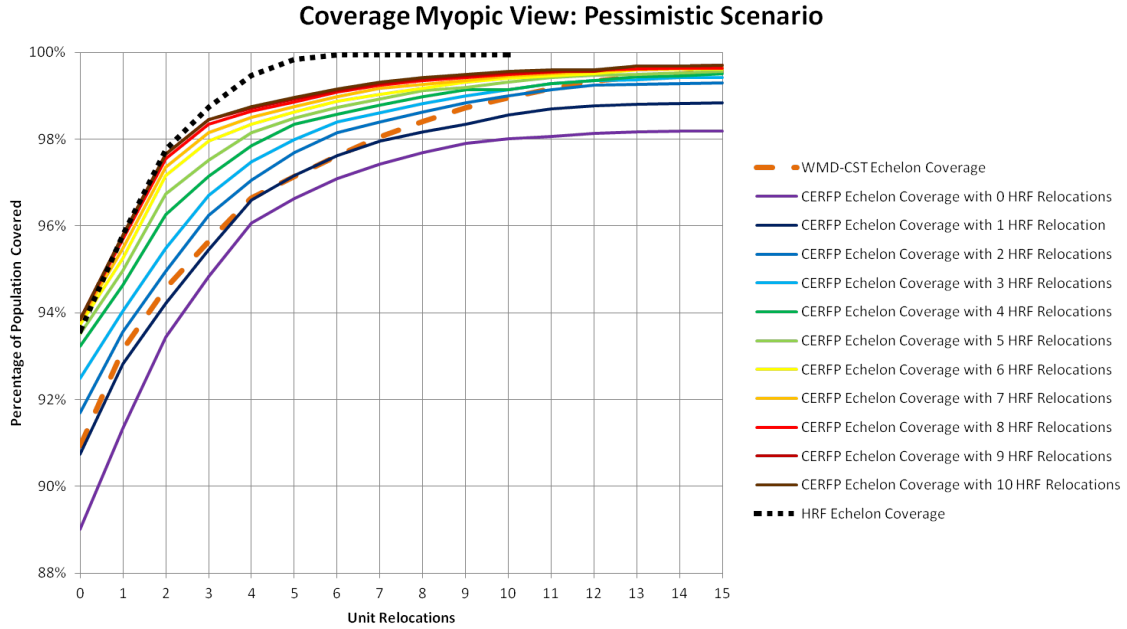
Figure 24. CRE coverage by echelon with CCP

4.8   Model Extension

We have examined how many additional teams are needed to achieve full coverage and how many relocations at each echelon are needed to achieve near-full coverage, but we have not analyzed if efficient gains in coverage can be achieved through additions and/or relocations. To identify solutions that answer this question, we develop an extension to our previous model. First, we introduce the following additional decision variables and parameters.

4.8.1 Decision Variables.

- x_a^ℓ : Number of teams added at echelon $\ell \in L$.

- x_r^ℓ : Number of teams relocated at echelon $\ell \in L$.

- z_i : A binary decision variable equal to 1 if demand at node i is covered by a facility at each echelon, and 0 otherwise, $\forall\, i \in D$.

4.8.2 Parameters.

- δ : Increase in coverage required to either relocate or add a team.

- c_a^ℓ : Cost to add a team at echelon $\ell \in L$.

- c_r^ℓ : Cost to relocate a team at echelon $\ell \in L$.

- B : Budget for unit relocations and additions.

- $\bar{z}$: Vector representing counties that are covered by current unit locations, 1 if a county is covered, 0 otherwise.

- ψ_j^ℓ : A Binary parameter equal to 1 if a unit at echelon ℓ is currently located at location j, 0 otherwise,

- p^ℓ : Number of current units at echelon ℓ.

4.8.3 Formulation.

$$\sum_{i \in D} h_i z_i - \delta \sum_{l \in L} \left(x_a^\ell + x_r^\ell \right) \geq \sum_{i \in D} h_i \bar{z}, \tag{4.1}$$

$$\sum_{j \in N} y_j^\ell - x_a^\ell \leq p^\ell, \qquad \forall \, \ell \in L, \tag{4.2}$$

$$\sum_{j \in N} \psi_j^\ell y_j^\ell + x_r^\ell \geq p^\ell, \qquad \forall \, \ell \in L, \tag{4.3}$$

$$\sum_{\ell \in L} \left(c_a^\ell x_a^\ell + c_r^\ell x_r^\ell \right) \leq B, \tag{4.4}$$

$$x_a^\ell \in \mathbb{Z}^+, \qquad \forall \, \ell \in L, \tag{4.5}$$

$$x_r^\ell \in \mathbb{Z}^+, \qquad \forall \, \ell \in L. \tag{4.6}$$

Constraint (4.1) requires the objective to improve by at least δ for a team to be either added or relocated. Constraint (4.2) bounds the number of teams at echelon ℓ by the current number of teams at that echelon plus the number added. Constraint (4.3) restricts the number of current unit locations in the solution to the current number of teams minus relocations. Constraint (4.4) restricts the total number of adjustments at all echelons. Finally, Constraints (4.5) and (4.6) restrict the number of teams added and relocated to be integer-valued.

4.8.4 Extension Application.

The extension is applied in a different manner for the WMD-CST only structure and the entirety of the CRE. This is done due to available data for cost estimations. WMD-CSTs were established as apart of the CRE and accurate cost estimates are available from the GAO [30]. The CERFP and HRF echelons were created from existing units which complicates estimating costs. Furthermore, there is limited open

source cost estimates available for either echelon. For this reason, we estimate cost parameters when applying the extension to the WMD-CST only structure but do not when applying the extension to the CRE in its entirety. The extension applied to the entire CRE uses simplified costs that treat each relocation and addition as equal at each echelon. While this is not the most accurate estimate, in general it is reasonable to assume minimizing total change is desirable.

4.8.5 Extension Applied to WMD-CST.

4.8.5.1 Parameter Estimation.

According to the 2006 GAO report [30], the cost of establishing the first 55 WMD-CSTs was $424 million. This equates to a cost of $7.7 million per team establishment. Given the current structure covers an estimated 278 million people, that entails an estimated fixed cost of $1.44 per person covered, not accounting for annual operational costs. If we apply the same cost per person to the uncovered population, which is approximately 27.8 million, we can establish an incremental expenditure that is equivalent to the initial expenditure in terms of cost per person. Based on this, we estimate the allowable incremental expenditure in order to achieve 100% coverage to be approximately $40 million. At $7.7 million per team, this results in a budget of establishing five new WMD-CSTs.

Given the WMD-CST structure currently in place, we note that additional teams will not increase coverage as efficiently as the first teams did; with 91% of the population already covered under the Pessimistic Scenario the efficiency of coverage for new teams will be significantly reduced. For this reason, we estimate the minimum population increase to be in line with the coverage provided by the ten teams that cover the fewest people within the current structure. We use three estimates, as depicted in Table 4.8.5.1: a maximum, average, and minimum population covered by

the least efficient WMD-CSTs in the current structure to denote considered values for δ.

Table 2. Estimates for Minimum Population Increase per Team Modification

Bottom 10 Teams	δ
Minimum	422,867
Average	2,013,113
Maximum	4,839,078

We also consider two possible situations: First, the cost of relocations is equal to the cost of establishing new teams, and second, the cost of relocations is half the cost of establishing a new team. Relocations do not require the fielding of new equipment or additional personnel, and thus may cost less.

Table 3. Equal Cost for Team Addition and Relocation

δ	x_a	x_r	Cost	Population Covered	Increase in Population Covered	Increase Per Cost
422,867	5	0	5	97.43%	6.50%	1.30%
2,013,113	5	0	5	97.43%	6.50%	1.30%
4,839,078	3	0	3	95.70%	4.77%	1.59%

In both situations, using the minimum or average δ, the model is bounded by Constraint (4.4), and we achieve the maximum increase in coverage. Using the maximum value of δ the model is bounded by Constraint (4.1) and yields the solution with the most cost-efficient solution. When relocations and additions have equal costs, the model only considers adding teams. This occurs because adding a team will always increase coverage by a value greater than or equal to the coverage added by relocating a team.

These estimates require verification from a subject matter expert prior to implementing any of these solutions, but the preceding analyses demonstrate how the parameters impact the output from the model extension.

Table 4. Team Addition is Half the Cost of Relocation

δ	x_a	x_r	Cost	Population Covered	Increase in Population Covered	Increase Per Cost
422,867	0	10	5	98.95%	8.01%	1.60%
2,013,113	0	10	5	98.95%	8.01%	1.60%
4,839,078	2	1	2.5	95.70%	4.77%	1.91%

4.8.6 Extension Applied to CRE.

As previously mentioned, there is limited information available to develop param-
eter estimates for the entire CRE structure. For this reason, we choose to generalize
the addition of a team as equally cost prohibitive and we seek to minimize the total
changes. We define the minimum increase per relocation to be at least 1 million
people. Using these parameters we highlight the trade-off in coverage as we increase
the limit on total modifications to the CRE structure.

Table 5. CRE Adjustments

Percent Covered	Total Adjustments	x_a^W	x_r^W	x_a^C	x_r^C	x_a^H	x_r^H
90%	5	1	1	2	0	0	1
92%	8	3	0	2	1	0	2
94%	11	1	2	2	2	0	4
96%	16	5	1	4	1	0	5
98%	20	7	1	4	2	0	6
99%	25	8	2	8	1	0	6

To achieve 98% coverage, a 15% increase from the current structure, we need to
relocate 9 CRE assets and add 11 CRE assets. We again note that these solutions
demonstrate the validity of the model, but more refined input is needed from subject
matter experts and decision makers to produce solutions that can guide changes to
the entire CRE structure.

4.9 Conclusion

In Chapter 4 we evaluated the coverage at the WMD-CST echelon and the CRE in its entirety. The WMD-CST analysis highlighted that the current coverage under the Baseline Scenario appears sufficient but improvements do exist. Application of the Pessimistic Scenario identified counties that have an increased risk level. While full coverage cannot be achieved by relocating every existing team, we can achieve 99% coverage with as few as ten WMD-CST relocations in either scenario. We further demonstrated the value of incorporating a pessimistic view into future modifications to the structure of the force. We also evaluated the sensitivity of the WMD-CST model to selected distance parameters.

The full CRE analysis also demonstrated improvements to the structure are possible. We again demonstrated the value of incorporating a pessimistic view into future planning considerations. We explored the resources needed for full coverage but determined they were cost prohibitive. A myopic view was used to explore how each echelon bounded the total coverage provided by the CRE.

Finally, we developed an extension to the model that maximizes coverage while balancing between additions and relocations, keeps modifications within a required budget, and ensures a minimum increase in coverage per change to the structure. Parameters were estimated to demonstrate the validity of this model.

V. Conclusions and Future Research

5.1 Conclusions

In this chapter, we summarize the major contributions of this research and propose directions for future research. This analysis demonstrated the value of applying previously proven facility location modeling techniques to evaluate and recommend improvements to the nation's CRE. With further input from subject matter experts and stakeholders, feasible solutions that further improve the CRE's coverage capabilities can be developed.

5.1.1 WMD-CST Structure.

The WMD-CST structural analysis found that sharing of WMD-CST assets across state boundaries greatly enhances the WMD-CST coverage capability. The current structure, using the existing definition of coverage, was found to be quite sufficient, covering approximately 95% of the population. Adjustments to the WMD-CST structure, however, most notably in Southern Florida, can increase the population covered by 12.6 million people to 99.99% total population covered. We also found every county in Florida and New York, states that both have fought to maintain two WMD-CST teams, could be covered with only one team located in each respective state.

The use of a Pessimistic Scenario demonstrated the effect of a 10 kiloton nuclear attack on the CRE's capability to rapidly respond. This analysis identified an additional 4% of the population, which includes 12 additional counties having a population greater than 250,000, that are uncovered if a CBRN attack were to neutralize CRE units within a 25 mile radius. Whereas the Pessimistic Scenario shows a significant reduction in coverage for current unit locations, there is only a 0.1% difference in population coverage for the optimal CRE locations between the two scenarios.

Furthermore, the Pessimistic Scenario reduces the risk to WMD-CSTs and improves the redundancy of coverage. Overall, the Pessimistic Scenario is a valuable planning consideration to incorporate in future modifications to the WMD-CST structure.

Because optimal solutions in both the Baseline and Pessimistic Scenarios may be cost prohibitive, we analyzed the trade-off between coverage and cost. We found near-full-coverage requires 25 to 32 moves for the Baseline and Pessimistic Scenarios, respectively. Most of the gain in coverage, however, can be achieved with less than a 20% modification to the WMD-CST structure. Finally, we examined the sensitivity of the model to the minimum stand-off distance and maximum coverage radius for the Pessimissitc Scenario and found coverage to be relatively insensitive to minor adjustments in the respective parameters.

5.1.2   CRE Structure.

The analysis of the entire CRE structure, using the Baseline Scenario, identified 35 million people to be living outside the rapid response window of at least one echelon of CRE units, to include 22 uncovered counties having populations greater than 250,000. An optimal placement of units significantly improves coverage, leaving only one county with a population exceeding 50,000 uncovered.

We again noted the advantage of the Pessimistic Scenario's optimal solution, as it yields a significant decrease in risk to CRE units and improves the percentage of the population that has redundant coverage. Furthermore, there is only a 0.27% reduction in total population coverage when comparing optimal solutions for the Pessimistic Scenario and Baseline Scenario.

The CERFP echelon was shown to have the greatest shortfall in coverage in both scenarios, implying it is the CRE echelon most in need of modifications to improve overall coverage.

5.1.3   Model Extension.

Given full coverage was cost prohibitive for the WMD-CST structure and the full CRE structure, we introduced a modeling extension that minimizes modifications to the structure but produces relatively large improvements in coverage. This modeling extension also accounts for different costs between adding and relocating teams, and it requires a minimum improvement to coverage to justify modifications to the structure. We developed model parameters for the WMD-CST structure based on existing cost estimates and demonstrated the usefulness of our modeling extension. The parameter estimates were developed differently for the full CRE due to limited cost information for the entire structure. Thus, we generalized cost estimates to assume all modifications to the structure are equally undesirable. Through this analysis we found the number of modifications needed to achieve different coverage levels; most notably, 98% coverage can be achieved with only 20 total adjustments to the CRE structure.

5.2   Directions for Future Research

We suggest the following areas to improve and/or extend the utility of this research.

5.2.1   Assumptions, Data, and Parameter Estimate Improvements.

Although our analysis provides significant insights, subject matter expert and stakeholder input is needed to refine assumptions, confirm or modify the network utilized, and validate parameter estimates.

First, we note the network was an estimation of the true network and is worth examining to ensure it sufficiently represents demands and facility locations. For example, the use of all counties as demands, especially those with populations under

50,000, may not provide enough focus on the demands with a much greater probability of attack. Second, some locations recommended as future CRE unit locations may not be feasible if CRE units are required to use existing federal or state facilities. Reducing possible facility locations to pre-approved CRE unit locations would result in solutions that need fewer modifications to implement. Finally, estimating current unit locations at population centers could introduce some error. Including the true locations would provide an increased level of confidence in the analysis. It should be noted this change would likely produce marginal differences to this analysis.

Another area for improvement is clarifying two assumptions related to the CERFP and HRF echelon. First, we assumed that a HRF could provide CERFP capability based on the HRF's structure but this should be confirmed by a subject matter expert. Second, the deployment procedures for CERFPs and HRFs is not explicitly defined in any doctrine or guidance that we reviewed. We assumed that the geographically dispersed CERFPs and HRFs would assemble at their respective CERFP or HRF headquarters and then deploy to an incident site. It is possible, however, that each component of a HRF or CERFP would assemble at their respective location and then assemble as a complete CERFP or HRF at a location closer to the incident. Clarifying this deployment process is necessary to more accurately represent response times and thus the coverage provided by a team.

5.2.2 Coverage Definition.

The binary coverage definition utilized provides useful information but is not the only technique for modeling coverage. It may be worth exploring the idea of changing the definition of coverage from binary to an indication of coverage efficiency. For example, using the binary definition, the coverage provided for a county that exists either one mile inside the coverage radius or one mile outside the coverage radius is

dramatically different. One location is fully covered and the other is not, but they only exist two miles apart from each other. Using a non-binary indicator can provide additional context to a county's level of coverage. Different coverage radii based on threat or population could also be used to prioritize the proximity of coverage to the most likely targets of a CBRN attack. The definition best suited for this analysis needs to be developed using input from the subject matter experts and stakeholders.

Appendix A. Storyboard

Bibliography

1. *Before disaster strikes: Imperatives for enhancing defense support to civil authorities.* Technical report, Advisory Panel on Department of Defense Capabilities for Support of Civil Authorities After Certain Incidents.

2. "Floridas WMD Disaster Response Unit Saved from Elimination". URL `http://dma.myflorida.com/floridas-wmd-disaster-response-unit-saved-from-elimination/`. Last accessed on 14 January 2014.

3. "Schumer, Gillibrand, Grimm Urge DOD & National Guard to Protect Terror Response Teams in New York, Including Fort Hamilton Team in Brooklyn". URL `http://www.gillibrand.senate.gov/newsroom/press/release/schumer-gillibrand-grimm-urge-dod-and-national-guard-to-protect-terror\-response-teams-in-new-york-including-forthamilton-team-in-brooklyn`. Last accessed on 14 January 2014.

4. "The U.S. Government Accountability Office: About GAO". URL `http://www.gao.gov/about/`. Last accessed on 14 January 2014.

5. *Department of Defense Plan for Integrating National Guard and Reserve Component Support for Response to Attacks Using Weapons of Mass Destruction.* Technical report, Department of Defense, 1998. URL `http://www.dod.mil/pubs/wmdresponse/`. Last accessed on 13 January 2015.

6. *Weapons of Mass Destruction Response Team Locations Announced.* Technical Report Press Release 512-98, US Department of Defense, 2001. URL `http://www.defense.gov/Releases/Release.aspx?ReleaseID=1857`. Last accessed on 13 January 2015.

7. *Catastrophic Disaster Response Staff Officer's Handbook.* Technical report, Center for Army Lessons Learned, 2006. URL `http://usacac.army.mil/cac2/call/docs/06-08/ap-h.asp`. Last accessed on 14 January 2014.

8. *2010 US Population by County.* Technical report, US Census Bureau, 2010. URL `http://www2.census.gov/geo/tiger/TIGER2010DP1/County_2010Census_DP1.zip`. Last accessed on 14 January 2014.

9. *County-to-County Distance Matrix.* Technical report, Center for Transportation Analysis, 2010. URL `http://cta.ornl.gov/transnet/SkimTree.htm`. Last accessed on 14 January 2014.

10. *Planning Guidance for Response to a Nuclear Detonation.* Technical report, Federal Interagency Committee Led by the Executive Office of the President, 2010.

11. *Chairman of the Joint Chiefs of Staff Instruction: Defense Response to Chemical, Biological, Radiological, and Nuclear (CBRN) Incidents in the Homeland.* Technical Report CJCSI 3125.01C, Department of Defense, 2012.

12. *National Preparedness Guidelines.* Technical report, Department of Homeland Security, 2012.

13. *Sustaining U.S. Global Leadership: Priorities for 21st Century Defense.* Technical report, Department of Defense, 2012.

14. *National Guard Bureau 2013 Posture Statement.* Technical report, National Guard Bureau, 2013.

15. *Strategy For Homeland Defense and Defense Support of Civil Authorities.* Technical report, Department of Defense, 2013. Http://www.defense.gov/news/homelanddefensestrategy.pdf.

16. *2013 NCHS UrbanRural Classification Scheme for Counties.* Technical report, US Department of Health and Human Services, 2014.

17. *DoD Strategy for Countering Weapons of Mass Destruction.* Technical report, Department of Defense, 2014.

18. *National Guard Bureau 2015 Posture Statement.* Technical report, National Guard Bureau, 2014.

19. "FEMA Regional Operations", 2015. URL `https://www.fema.gov/regional-operations`. Last accessed on 09 February 2015.

20. Badri, Masood A., Amr K. Mortagy, and Colonel Ali Alsayed. "A multi-objective model for locating fire stations", *European Journal of Operational Research*, 110(2):243–260, 1998.

21. Belardo, Salvatore, J. Harrald, William A. Wallace, and J. Ward. "A partial covering approach to siting response resources for major maritime oil spills", *Management Science*, 30(10):1184–1196, 1984.

22. Berman, Oded, Zvi Drezner, and Dmitry Krass. "Generalized coverage: New developments in covering location models", *Computers & Operations Research*, 37(10):1675–1687, 2010.

23. Berman, Oded and Dmitry Krass. "The generalized maximal covering location problem", *Computers & Operations Research*, 29(6):563–581, 2002.

24. Besosa, Miguel A. *The Role of the National Guard in Responding to Weapons of Mass Destruction (WMD) Attacks in the US: Where Do We Stand?* Master's thesis, Air Command and Staff College, 2001.

25. Brown II, LTC Robert W. *National Guard Weapons of Mass Destruction Civil Support Teams–Are They Ready.* Technical report, 2004.

26. Chaudhry, Sohail S., I. Douglas Moon, and S. Thomas McCormick. "Conditional covering: greedy heuristics and computational results", *Computers & operations research*, 14(1):11–18, 1987.

27. Church, Richard and Charles ReVelle. "The maximal covering location problem", *Papers in regional Science*, 32(1):101–118, 1974.

28. Cohon, Jared L. *Multiobjective programming and planning.* Courier Dover Publications, 2013.

29. Current, John, Hokey Min, and David Schilling. "Multiobjective analysis of facility location decisions", *European Journal of Operational Research*, 49(3):295–307, 1990.

30. D'Agostino, Davi M. *Homeland Defense: National Guard Bureau Needs to Clarify Civil Support Teams Mission and Address Management Challenges.* Technical Report GAO-06-498, The U.S. Government Accountability Office, 2006.

31. D'Agostino, Davi M. *Homeland Defense: Preliminary Observations on Defense Chemical, Biological, Radiological, Nuclear, and High-Yield Explosives Consequence Management Plans and Preparedness.* Technical Report GAO-09-927T, The U.S. Government Accountability Office, 2009.

32. D'Agostino, Davi M. *Planning, Resourcing, and Training Issues Challenge DOD's Response to Domestic Chemical, Biological, Radiological, Nuclear, and High-Yield Explosive Incidents.* Technical Report GAO-10-123, The U.S. Government Accountability Office, 2009.

33. Daskin, Mark S. "A maximum expected covering location model: formulation, properties and heuristic solution", *Transportation Science*, 17(1):48–70, 1983.

34. Daskin, Mark S. *Network and discrete location: models, algorithms, and applications.* John Wiley & Sons, 2011.

35. Department of Defense. *Joint Publication 3-41: Chemical, Biological, Radiological, and Nuclear Consequence Management*, June 2012.

36. Eckman, Dwayne P. Phone Conversation, August 2014.

37. Erichsen, Sven C. *National Guard Weapons of Mass Destruction Civil Support Teams: Performing as Required?* Master's thesis, United States Army Command and General Staff College, 2002.

38. Farahani, Reza Zanjirani, Nasrin Asgari, Nooshin Heidari, Mahtab Hosseininia, and Mark Goh. "Covering problems in facility location: A review", *Computers & Industrial Engineering*, 62(1):368–407, 2012.

39. Francis, Richard L., John A. White, and Leon Franklin McGinnis. *Facility layout and location: an analytical approach*, volume 31. Prentice-Hall Englewood Cliffs, NJ, 1974.

40. Gendreau, Michel, Gilbert Laporte, and Frédéric Semet. "Solving an ambulance location model by tabu search", *Location science*, 5(2):75–88, 1997.

41. Giles, Spencer W. *National Guard Weapons of Mass Destruction Civil Support Teams: How Practical is Cost Saving Reduction?* Master's thesis, United States Army Command and General Staff College, 2013.

42. Hagel, Chuck. *2014 Quadrennial Defense Review*. Technical report, Department of Defense, 2014.

43. Hakimi, S. Louis. "Optimum locations of switching centers and the absolute centers and medians of a graph", *Operations Research*, 12(3):450–459, 1964.

44. IBM. "CPLEX Optimizer", 2012. V12.6.0.

45. Jia, Hongzhong, Fernando Ordóñez, and Maged Dessouky. "A modeling framework for facility location of medical services for large-scale emergencies", *IIE Transactions*, 39(1):41–55, 2007.

46. Klose, Andreas and Andreas Drexl. "Facility location models for distribution system design", *European Journal of Operational Research*, 162(1):4–29, 2005.

47. Kolesar, Peter and Warren E. Walker. "An algorithm for the dynamic relocation of fire companies", *Operations Research*, 22(2):249–274, 1974.

48. Larson, Eric V. and John E. Peters. *Preparing the US Army for Homeland Security: Concepts, Issues, and Options*. Rand Corporation, 2001.

49. Lunday, Brian J. *The modified covering problem on paths and trees*. Master's thesis, The Univeristy of Arizona, 2001.

50. Moon, I. Douglas and Sohail S. Chaudhry. "An analysis of network location problems with distance constraints", *Management Science*, 30(3):290–307, 1984.

51. Murali, Pavankumar, Fernando Ordóñez, and Maged M Dessouky. "Facility location under demand uncertainty: Response to a large-scale bio-terror attack", *Socio-Economic Planning Sciences*, 46(1):78–87, 2012.

52. Murty, Katta G. and Philipp A. Djang. "The US Army national guard's mobile training simulators location and routing problem", *Operations Research*, 47(2):175–182, 1999.

53. Myers, Raymond H., Douglas C. Montgomery, and Christine M. Anderson-Cook. *Response surface methodology: process and product optimization using designed experiments*, volume 705. John Wiley & Sons, 2009.

54. National Guard Bureau. *National Guard Regulation 500-4: National Guard CBRNE Enhanced Response Force Package Management*, October 2009.

55. National Guard Bureau. *National Guard Regulation 500-3: Weapons of Mass Destruction Civil Support Team Management*, May 2011.

56. Pirkul, Hasan and David A. Schilling. "The maximal covering location problem with capacities on total workload", *Management Science*, 37(2):233–248, 1991.

57. Plane, Donald R. and Thomas E. Hendrick. "Mathematical programming and the location of fire companies for the Denver fire department", *Operations Research*, 25(4):563–578, 1977.

58. Schilling, David A., Vaidyanathan Jayaraman, and Reza Barkhi. "A Review of Covering Problems in Facility Location", *Computers & Operations Research*, 1993.

59. St. Laurent, Janet A. *Homeland Defense and Weapons of Mass Destruction: Additional Steps Could Enhance the Effectiveness of the National Guard's Life-Saving Response Forces*. Technical Report GAO-12-114, The U.S. Government Accountability Office, 2011.

60. Toregas, Constantine, Ralph Swain, Charles ReVelle, and Lawrence Bergman. "The location of emergency service facilities", *Operations Research*, 19(6):1363–1373, 1971.

61. Van Alstyne, Christian M. *Potential standards and methods for the National Guard's homeland response force*. Master's thesis, Naval Postgraduate School, 2011.

REPORT DOCUMENTATION PAGE

1. REPORT DATE *(DD–MM–YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From — To)*
26–03–2015	Master's Thesis	Sept 2013 — Mar 2015

4. TITLE AND SUBTITLE

Optimizing the Domestic
Chemical, Biological, Radiological, and Nuclear
Response Enterprise

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Paul, Nicholas R., Captain, USA

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Institute of Technology
Graduate School of Engineering and Management (AFIT/EN)
2950 Hobson Way
WPAFB OH 45433-7765

8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT-ENS-MS-15-M-143

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Intentionally Left Blank

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Distribution Statement A:
Approved for Public Release; distribution unlimited.

13. SUPPLEMENTARY NOTES

This work is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

14. ABSTRACT

The Chemical Biological Radiological Nuclear (CBRN) Response Enterprise (CRE) exists to rapidly respond to a domestic CBRN attack in order to minimize the overall impact of an incident. Over the past 16 years, the CRE has grown incrementally, and it is unclear if the current locations of units optimizes the coverage of the US population within a rapid response window. In this paper we develop a multi-objective multi-service extension of the maximal covering location problem (MCLP) to analyze the current coverage provided by the CRE and recommend efficient modifications to better protect the American population. While public sector facility location problems are well studied, the significant damage created by a CBRN attack requires unique modeling considerations. Most notably, we model the impact to coverage when CRE units within a minimum stand-off distance are rendered non-functional by a CRBN attack using an adaptation of the conditional covering problem (CCP). This minimum stand-off distance is not currently a consideration in existing Department of Defense (DoD) doctrine or planning guidance, but through a comparison to the current DoD definition of coverage we demonstrate the value of incorporating this concept into future planning considerations. Finally, we account for the multi-objective nature of this problem by developing a set of non-inferior solutions that allow a decision maker to apply their judgment to balance the trade-off between coverage and cost.

15. SUBJECT TERMS

maximal covering location problem (MCLP); conditional covering problem (CCP); CBRN; WMD-CST; HRF; CBRN Response Enterprise (CRE); CERFP; coverage; multi-objective; epsilon constraint method

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			LTC Brian L. Lunday, AFIT/ENS
U	U	U	UU	116	19b. TELEPHONE NUMBER *(include area code)* (937) 255-3636, x4624; Brian.Lunday@afit.edu